HAGIA SOPHIA FROM THE AGE OF JUSTINIAN TO THE PRESENT

EDITED BY
ROBERT MARK AND AHMET Ş. ÇAKMAK

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To
Robert Van Nice

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PREFACE

With its vast scale, immense cost, extraordinary speed of erection, and stunning interior space, the Hagia Sophia, constructed between 532 and 537, is unparalleled in premodern Western architecture. As such, the creation of this great building begs answers to three important and interrelated questions. The first of these falls mainly in the realm of architectural-technological history and concerns the nature of the theoretical and material resources available to the early designers. The second concerns the behavior over the centuries of Hagia Sophia's much-modified structure under the action of environmental loadings, including earthquakes. The third question, the answer to which is directly related to that of the second, concerns the capacity of the present-day structure to withstand a major earthquake – an event likely to occur during the next half-century.

To begin to address these questions, a colloquium was convened to focus on the fabric of Hagia Sophia and related buildings. Cosponsored by the Princeton schools of Architecture and of Engineering and Applied Science, the departments of Art and Architecture and of Near Eastern Studies, the programs in Hellenic Studies and in the History, Archaeology, and Religions of the Ancient World, and the Committee for Medieval Studies, it brought together scholars and professionals from different disciplines to exchange ideas and new information pertaining to historical background, physical environment, design, and the state of the building structure over time. The colloquium was accompanied by an exhibit of photographs entitled "Hagia Sophia, 1989" by J. Wayman Williams, Jr., and a scale model of the early building constructed by Denise Dumais, a graduate student in the School of Architecture.

A longer-range goal of the colloquium was to provide a sound basis for a new study being undertaken by the Architecture School together with the Earthquake Engineering Group, within Princeton's Department of Civil Engineering and Operations Research, and the Earthquake Research Institute of Kandilli Observatory in Istanbul that will use data from on-site dynamic instrumentation and archaeology to guide the development of a comprehensive

numerical (computer) model of the Hagia Sophia structure. Far less sophisticated engineering studies of monumental buildings correlated with archaeological examination have already made important contributions to the work of the historian. In the absence of documents detailing the sequence of construction, it is usually possible to determine the order of building from subtle changes in structure or alignment from one part of a building to another. This information, complemented by linear–elastic modeling (which signals weaknesses arising also with nonlinear–inelastic behavior), can often clarify the function of structural elements and shed light on the structural perceptions of the early designers and their design techniques. More recently, structural modeling has been applied to the restoration of early buildings.[1] To insure against subsequent structural failure, and the possibility of serious injury both to the monuments and to their visitors, the models employed for restoration studies ought to encompass the sequence of building construction, the nonlinear range of building material behavior, and loadings that may not have been envisioned by the original designers, including those of an earthquake. The new generation of numerical-modeling approaches, which should provide reliable predictions of the full range of structural behavior of large-scale historic buildings under dynamic as well as static loadings, may well prove invaluable to future restoration projects. Yet one should be mindful that such model studies can fulfill a dual role. In addition to helping pinpoint immediate structural problems and suggesting solutions to the problem of preservation, when interpreted in an appropriate historical context they can also reveal the structural intentions of the original designers – knowledge that can be just as important for determining restoration strategy as for understanding any other facet of early building planning.[2]

The colloquium essays are organized along several common themes: structural precursors of Hagia Sophia; observations on the fabric of the Byzantine Hagia Sophia and related buildings; structural studies of Hagia Sophia and related buildings; and the Ottoman Hagia Sophia and its influence on contemporaneous architecture. The essays concerned with the first theme are those by William L. MacDonald, on the architectural lineage of Hagia Sophia as partly contained in the continuing, grand Roman experimental tradition; and by Slobodan Ćurčić, on the general, fundamental principles understood by fifth-century Byzantine builders and their bearing on certain design choices that ultimately led to the creation of Hagia Sophia.

Observations on building fabric include those of early commentators described by Cyril Mango in his concise survey of Byzantine literature on Hagia Sophia with particular emphasis on Procopius and the *Diegesis*. In addition, Lawrence E. Butler discusses the nave cornices of Hagia Sophia as an important, accessible, little-studied part of the fabric yielding information concerning the architects' intentions and sequence of construction. Onur Gürkan,

1 See, e.g., R. M. Lemaire and K. Van Balen, eds., *Stable–Unstable: Structural Consolidation in Ancient Buildings* (Leuven, 1988); I. Mungan, ed., *Domes from Antiquity to the Present*, Proceedings of the 1988 International Symposium, IASS (Istanbul, 1988); and C. A. Brebbia, ed., *Structural Repair and Maintenance of Historic Buildings* (Basel, 1989).

2 Unfortunately, architects and engineers concerned with building restoration have tended to disregard the historiographic inferences to be gained from their structural studies. See, e.g., B. M. Feilden, *Between Two Earthquakes: Cultural Property in Seismic Zones* (Marina del Rey, Calif., 1987), esp. 87–91.

Serhat Çamlıdere, and Mustafa Erdik outline a preliminary, three-dimensional geodesic survey of the great dome and curve fitting of a spherical surface. Finally, Kalliope Theocharidou describes the structural history of Hagia Sophia in Thessaloniki, including observations on its foundations, construction materials, and techniques, as well as the structure and its defects.

The structural studies include the essay of Shiro Kato, Takayoshi Aoki, Kenichiro Hidaka, and H. Nakamura on finite-element modeling of the domes of Hagia Sophia, as well as that of Robert Mark, Ahmet Ş. Çakmak, and Mustafa Erdik on the first stages of an integrated model study of Hagia Sophia that reflects the sequence of construction and subsequent physical history, as well as data from dynamic instrumentation installed in the building fabric. In addition, George Penelis, Maria Karaveziroglou, Kosmas Stylianidis, and Demitrios Leontaridis discuss the seismic behavior of the Rotunda of Thessaloniki and the structural interventions made in response to the serious earthquake damage suffered by this monument in June 1978. A critical appraisal of past and present structural studies of Hagia Sophia is presented by Rowland J. Mainstone.

The final theme – Ottoman Hagia Sophia and its influence – is addressed by Metin Ahunbay and Zeynep Ahunbay in their essay on the Ottoman mosques directly influenced by Hagia Sophia's structure and architectural design as well as by Gülru Necipoğlu, who explores the mythification, reception, and structural/decorative transformation of Hagia Sophia from Ottoman narrative histories and archival documentation.

Our ability to hold a colloquium of this nature on Hagia Sophia is in large part a tribute to the life work of architect Robert Van Nice, to whom this book is dedicated. Long affiliated with Dumbarton Oaks, he began in 1937, together with William Emerson of MIT, the first modern survey of the building fabric of Hagia Sophia. Generations of architectural historians will be indebted to Van Nice (and to Dumbarton Oaks) for his two volumes of survey drawings, the first published in 1965 and the second in 1980. Selected drawings from these volumes are included here in an appendix.

The editors express their deep appreciation to Angeliki E. Laiou, director of Dumbarton Oaks, for granting permission to reissue the Van Nice survey drawings. We are grateful for vital assistance given in the production of this volume by Robert O. Bork, Linda Komaroff, Claudia Marchitiello Mark, and Andrew J. Tallon and in the planning of the colloquium by the faculty steering committee: Slobodan Ćurčić, representing the Department of Art and Archaeology, who together with Amy Cassens designed the exhibit; Abraham L. Udovitch, Near Eastern Studies; Dimitri H. Gondicas, Hellenic Studies; Hugo Meyer, History, Archaeology, and Religions of the Ancient World; William C. Jordan, Medieval Studies; and Carol Rigolot, the Council of the Humanities. We also acknowledge the beneficence of Theodore J. Ziolkowski, dean of the Graduate School. In addition to its cosponsors, financial support for the colloquium and the exhibition came from a grant by the Andrew W. Mellon Foundation to Princeton University and the President's Fund of Princeton University.

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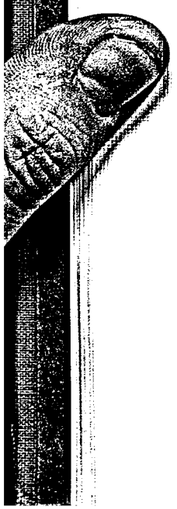
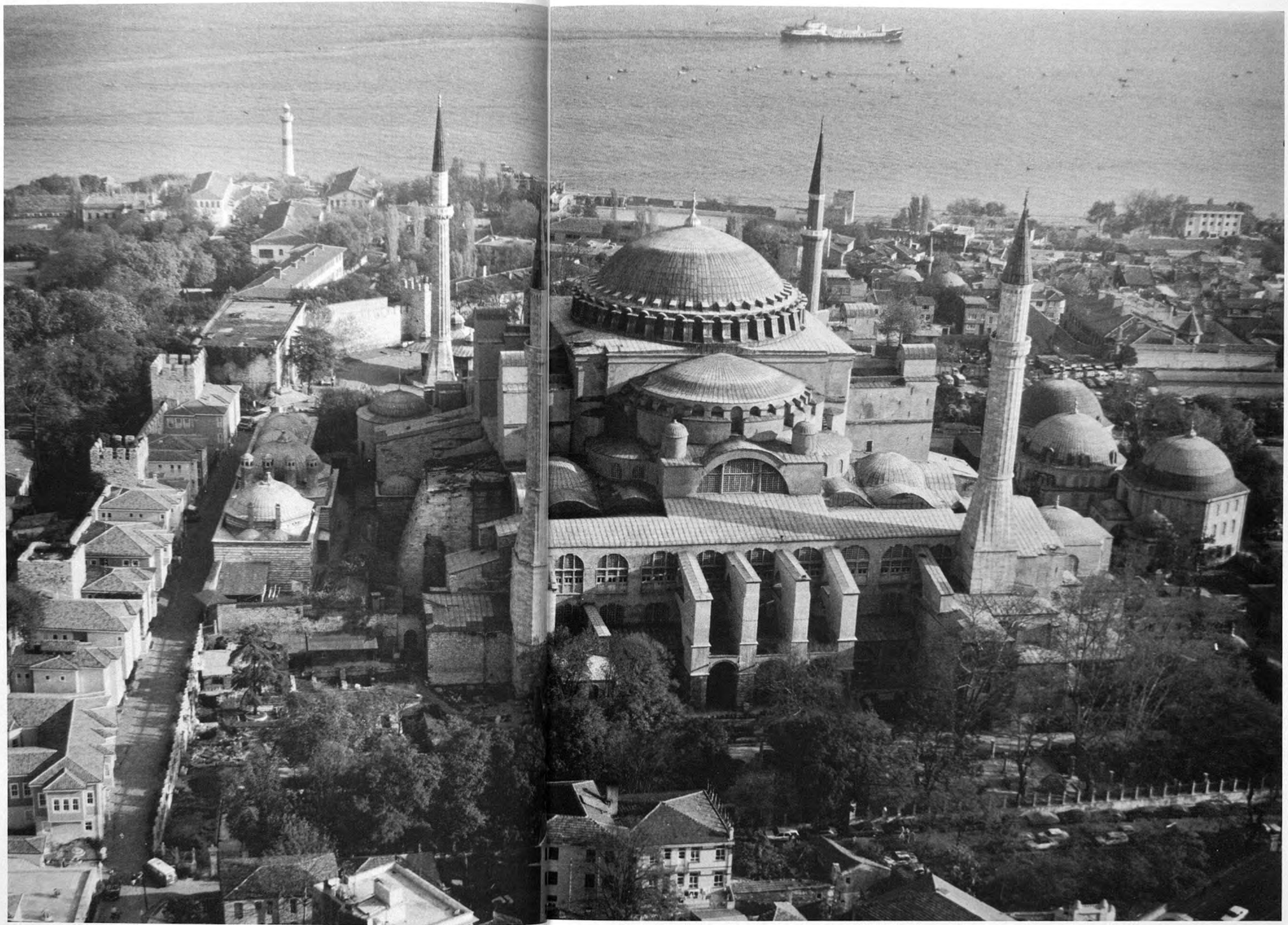
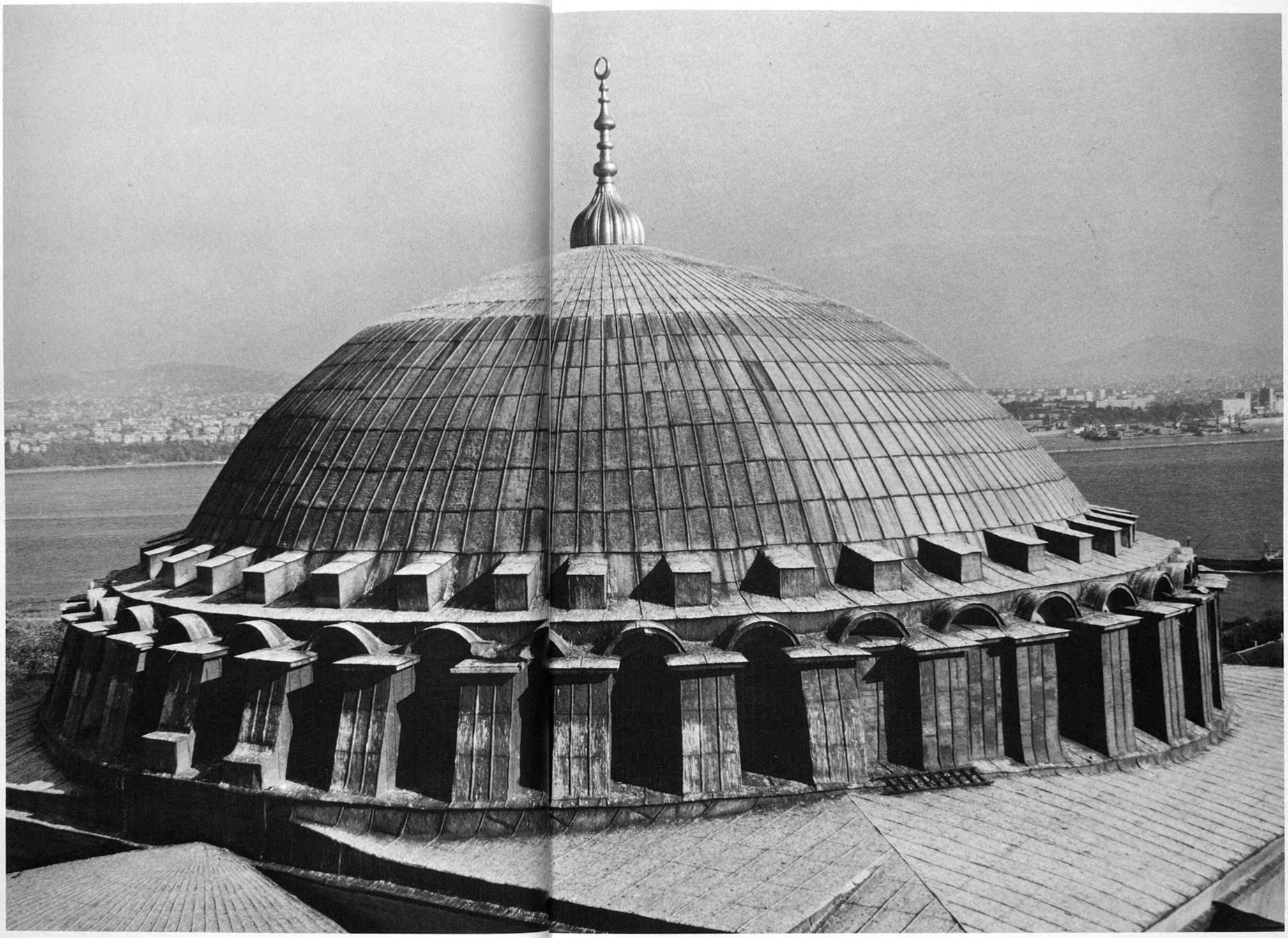


HAGIA SOPHIA
PHOTOGRAPHIC ESSAY

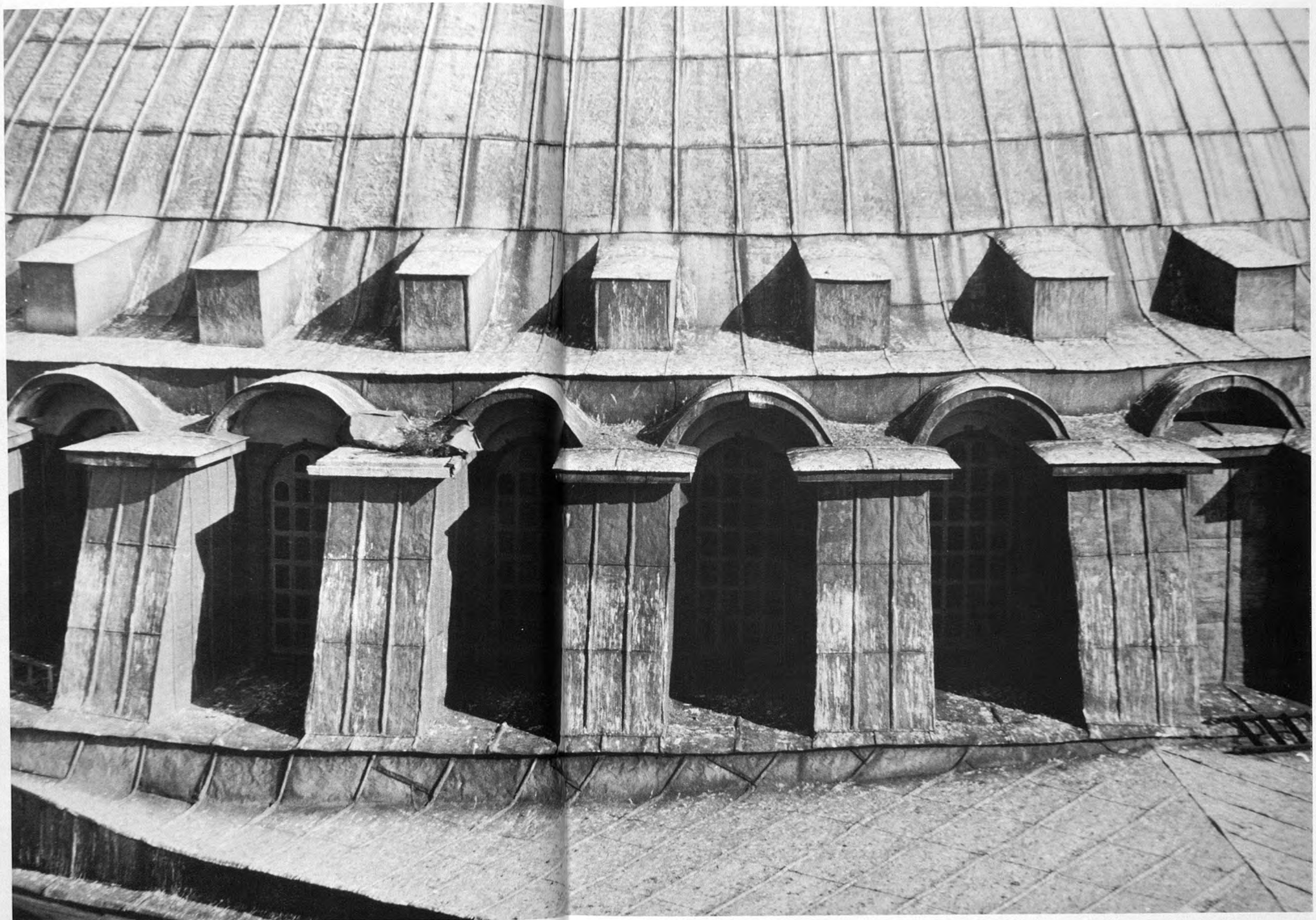
J. WAYMAN WILLIAMS, JR.



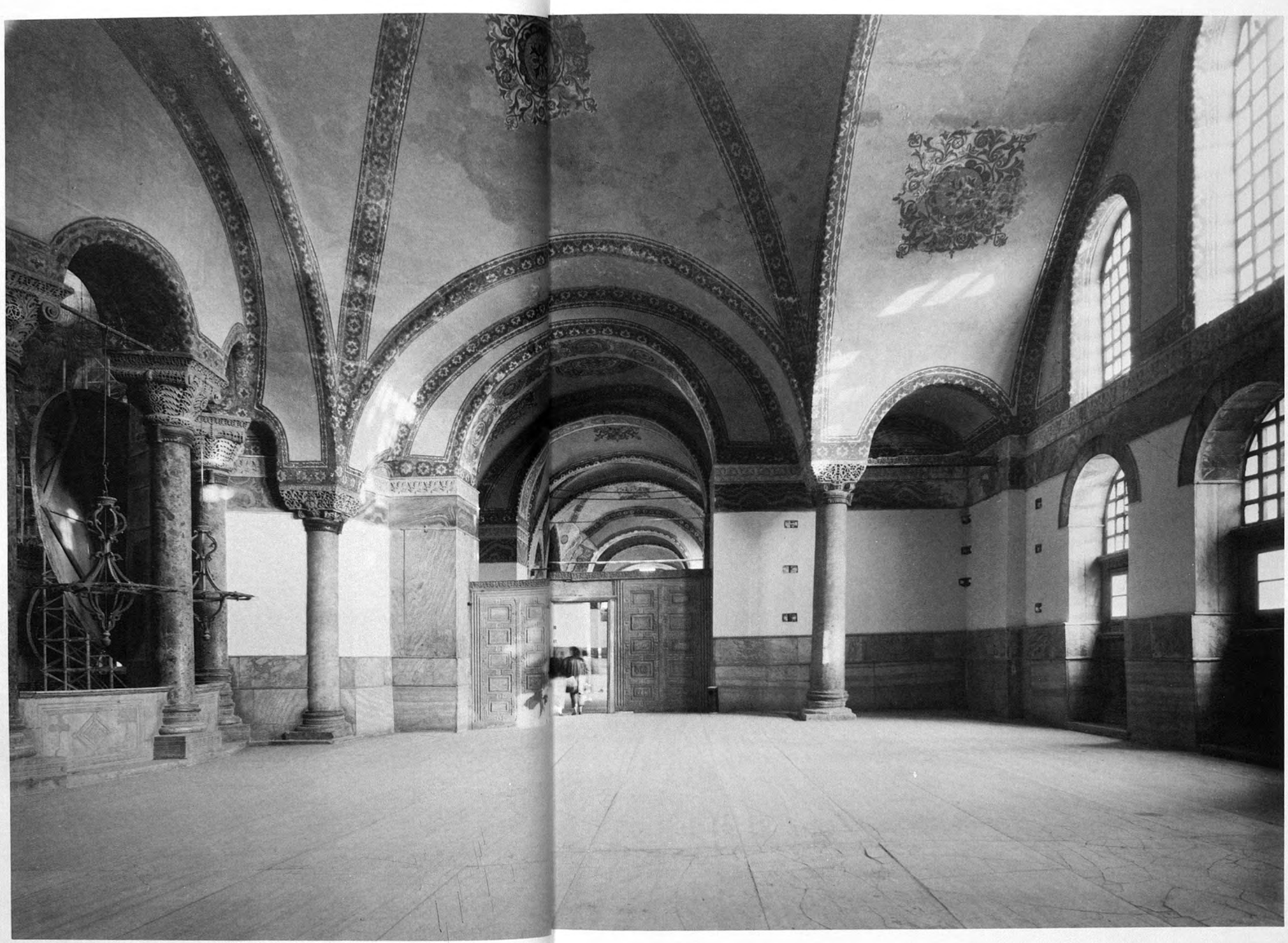
Hagia Sophia, Istanbul, 532–7; view from the west



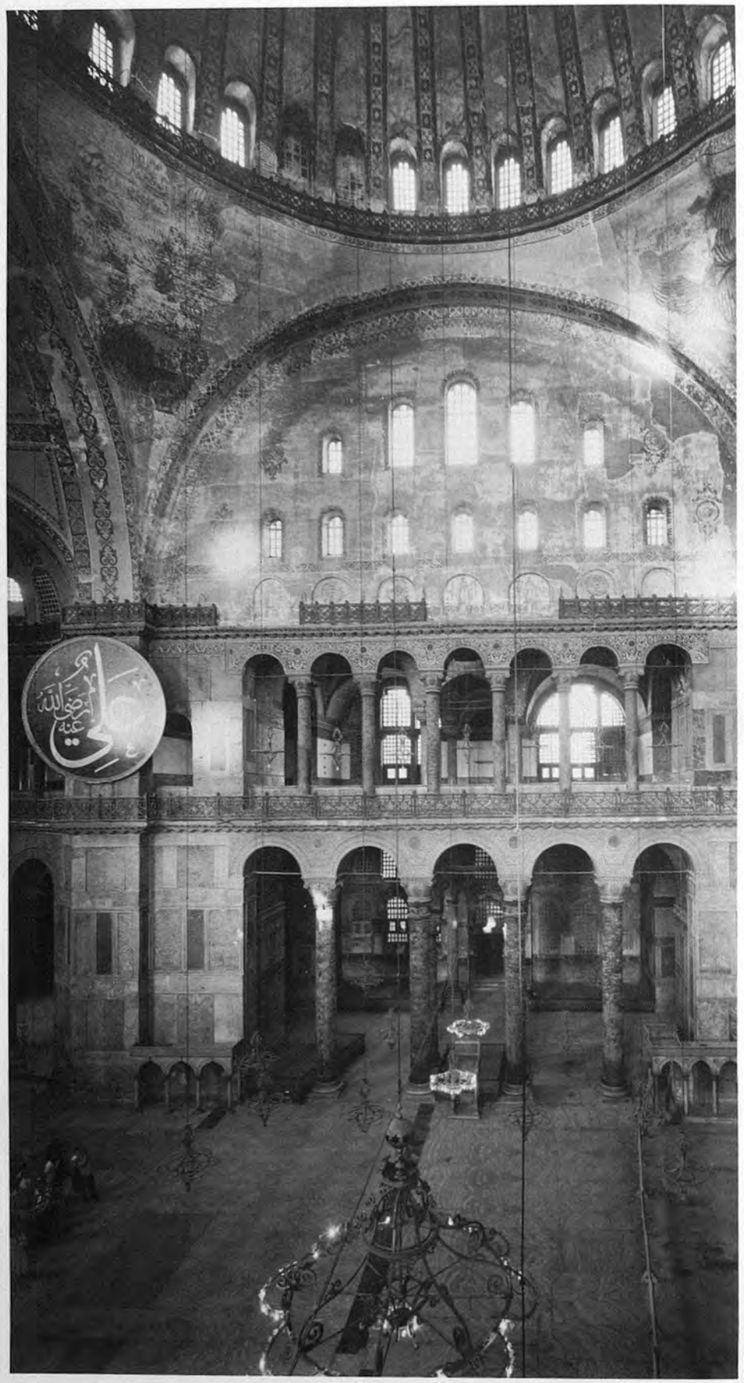
Central dome and base from southwest minaret



Detail of windows around the central dome

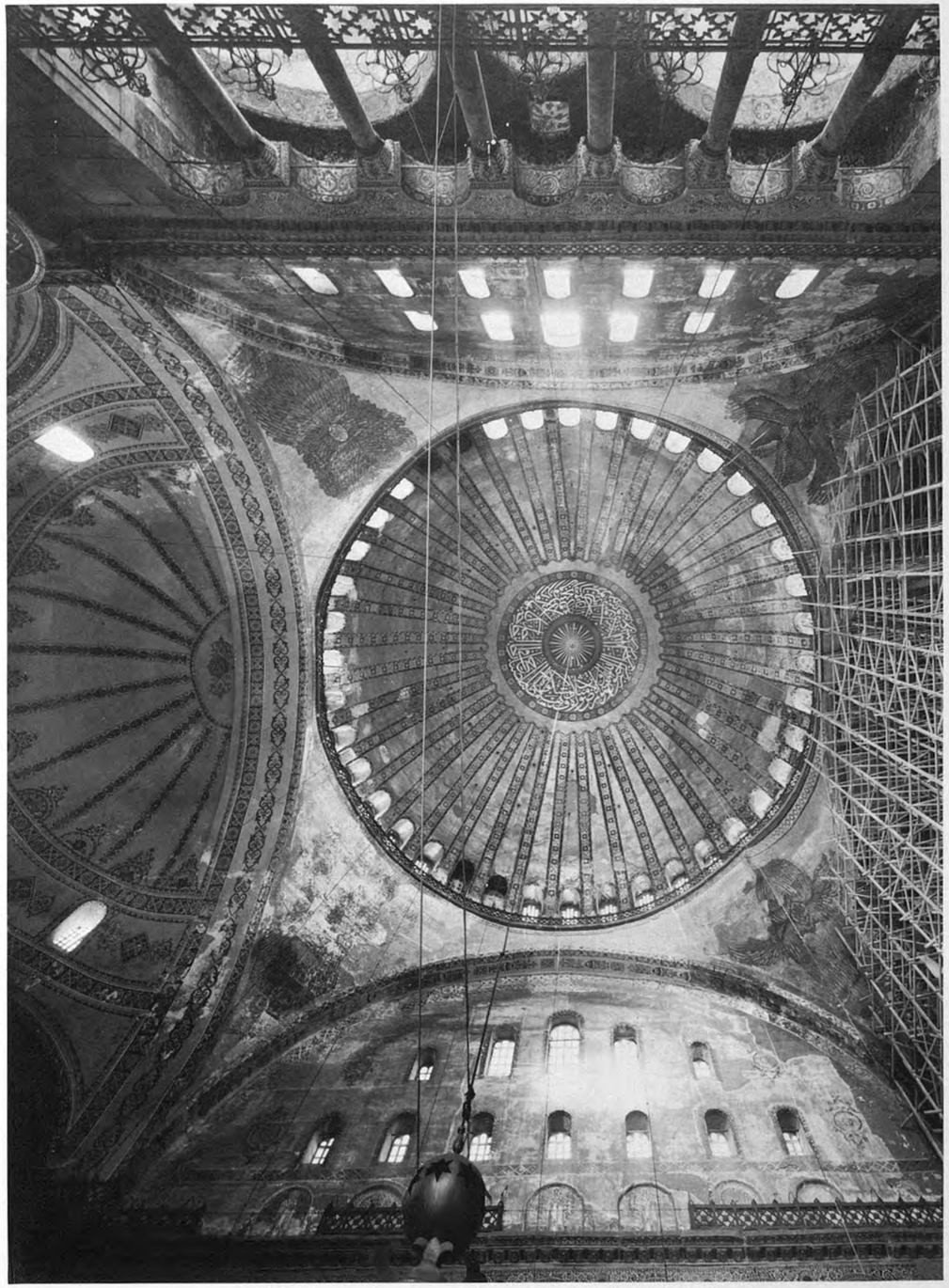


Southeast gallery

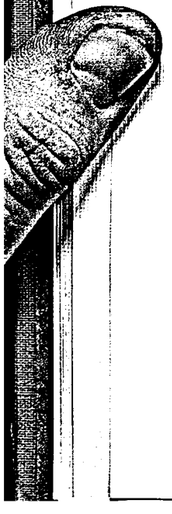


Interior looking north

View of the dome, western semidome, and tympani



STRUCTURAL PRECURSORS OF HAGIA SOPHIA



ROMAN EXPERIMENTAL DESIGN AND THE GREAT CHURCH

WILLIAM L. MACDONALD

The architect who designed the Tabularium in Rome in 78 B.C. changed architecture. He married the Greek stoa's potent symbolism with both the previously utilitarian Roman arcade and a file of vaulted, spatial cells to create an enduring backdrop for the Forum below. Though similar forms could be seen at the recently completed sanctuaries of Tivoli and Praeneste, they were not independent structures but were embedded in the grand schemes to which they took second place, with the orders treated as wall elements rather than as descendants of sharp-edged, lustrous Greek forms. Up on the Capitoline shoulder, the Tabularium was an independent entity, both scenic and functional,[1] whose arcaded gallery records the most advanced architectural thinking of the day (Figure 1).

Behind the original ten facade arches, 7.5 m (25 Roman feet) high and about half as wide, the corresponding vaulted cells are marked off by transverse arches carried on short spur walls in the manner of attached piers. These arches, like those of the windows and of the corresponding openings (now blocked) along the gallery back wall, carry low walls from whose square openings the concrete vaults rise.[2] Though much restored, these are clearly cloister vaults, made of concrete in almost exactly the same way as those that survive, unrestored at the Sanctuary of Hercules at Tivoli. Thus, in plan, the gallery is made up of iterated, cross-shaped piers (the engaged facade columns are part of this scheme); in elevation, the vault crowns rise 10.5 m (35 Roman feet) above the pavement. Because the gallery structure is thus compartmentalized, each cell maintains a degree of independence while the functional continuity of the whole remains intact. And the inward stance of the spur walls

1 G. Lugli, *Roma antica: Il centro monumentale* (Rome, 1946), 42–6; E. Nash, *Pictorial Dictionary of Ancient Rome*, 2d ed. (London, 1968), 402–8. For the vaults, M. E. Blake, *Ancient Roman Construction in Italy from the Prehistoric Period to Augustus* (1947), 331; they are not domical, as claimed by A. Boëthius, *Etruscan and Early Roman Architecture* (Harmondsworth, 1978), 2d ed., 145, 156.

2 On the influence of the Tabularium vaults, F. E. Brown, personal communication; on Apollodorus and Hadrian's vaults, idem, "Hadrianic Architecture," in *Essays in Memory of Karl Lehmann*, ed. L. F. Sandler (New York, 1964), 55–8.

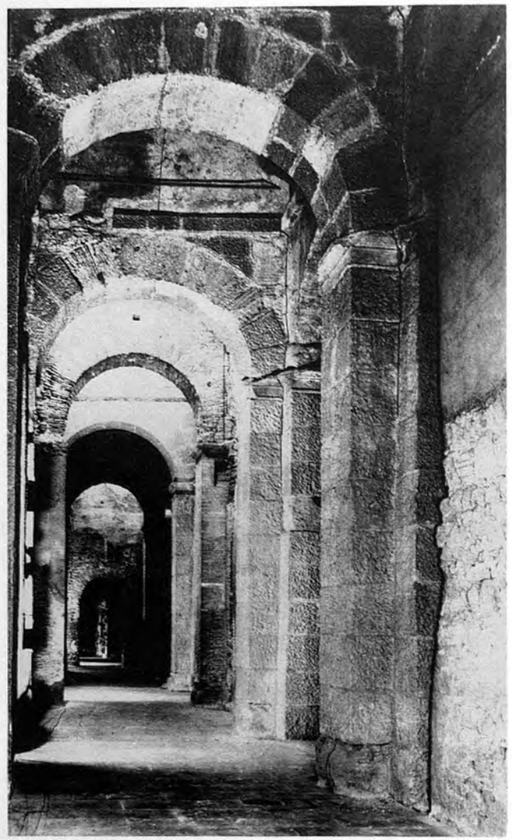


Fig. 1. The Tabularium, Rome, 78 B.C.; the gallery interior. (Fototeca Unione)

transforms what could easily have been a single, barrel-vaulted space into a rhythmically articulated, interesting yet axial design. The big windows give ample light and frame broad views out over the Forum, and all in all the building is an original urban creation, a distant forerunner of the Great Church's inner narthex (Figure 2).

The results typify Roman experimentalism. Past design elements (the orders, the arch) are adapted to new uses, the roles of traditional materials (stone, concrete) are expanded, and the structural framework of the building not only is clearly and meaningfully stated and fully integrated into the overall design but also records a novel statement of that quality of iteration essential to classical architecture. The gallery's position on the hill and its visual connection with the Forum declare its significance, while its urban purpose (circulation among the city records offices) is efficiently served. History has been reshaped, in great part because the architect saw in the simple cloister vault a fine opportunity for innovation. That his design may have evolved from a need to buttress and support the structures beyond and above the gallery does not detract from his originality.

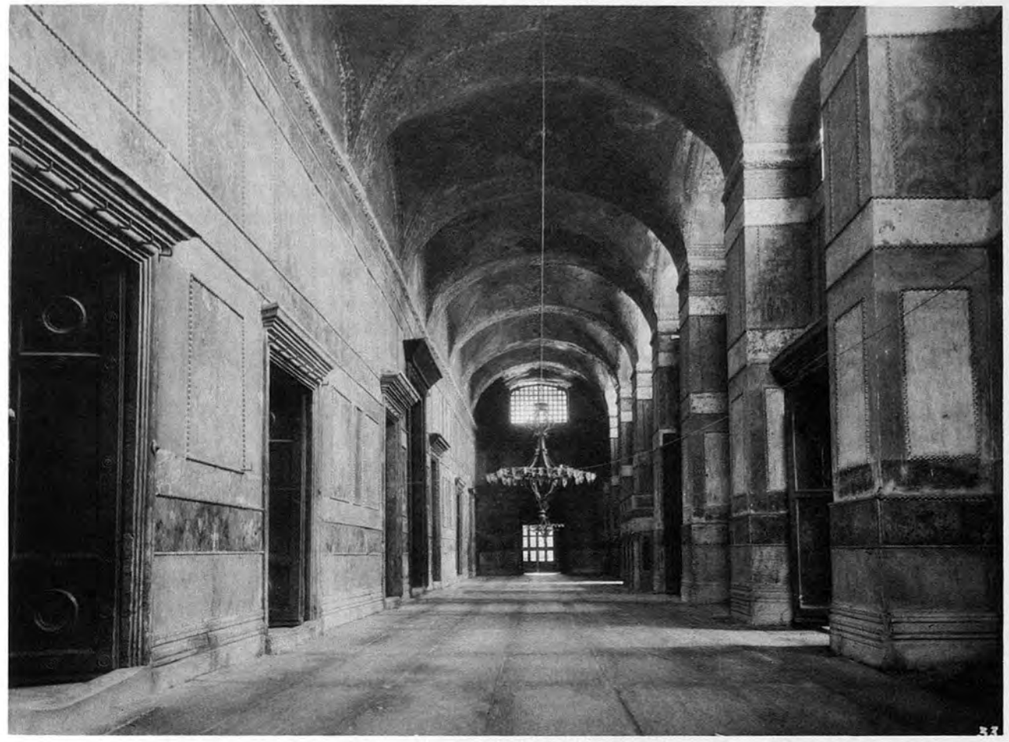


Fig. 2. The Great Church, Istanbul, A.D. 532–7; the inner narthex.

It was the late Frank Brown who pointed out that these vaults were the forerunners of Roman and later segmented ones; he saw that the conceptual principle involved was the same as that seen, for example, in larger and more sophisticated vaults at Baiae, Bulla Regia, or Hadrian's Villa near Tivoli; there are numerous others. In a brilliant article he connected these segmented surfaces with the famous gourds invoked by Trajan's architect in chief Appolodorus, who, when dismissing criticism by Hadrian, referred to the latter's interest in drawing such forms.[3] Certainly Hadrianic buildings preserve them; perhaps other evidence exists, as in the multiple intersections of different vault surfaces in the Markets of Trajan or the Baths of Caracalla. Here the point is that Roman architecture was mired in neither tradition nor nostalgia, as segmented vaults, which may seem routine and inconsequential to some, clearly show: The Tabularium gallery can properly be taken as the starting point of a grand architectural tradition of experimental design. That this runs somewhat contrary to the generally accepted version of the trajectory of Roman architecture under the empire requires some brief comment.

Within this vast subject[4] the guiding category has usually been typology,

3 Ibid.

4 Nash, *Pictorial Dictionary;* J. B. Ward-Perkins, *Roman Imperial Architecture* (Harmondsworth, 1981); W. L. MacDonald, *The Architecture of the Roman Empire,* vol. 1, *An Introductory Study* (New Haven, Conn., 1982).

that is, classification by function, with trends in style and structural methods seen as regional events. Both are saddled with Vitruvianism,[5] which is the very risky application of conservative Vitruvian dicta to buildings built well after his time, and with an odd faith in the idea that major changes came and went with the accession and departure of emperors. Typology is a jealous master, by nature inhospitable to unusual and unexpected variations within a building type, and as readily produces a scholars' norm as the Corinthian capital, whose very nature and purpose preclude formal standardization.

It was natural for humanist scholars and architects to search for norms and to apply Vitruvius's words to what could be seen, but it is clear now that this had a stultifying effect on Roman studies, unfortunately still with us. In the seventeenth and eighteenth centuries very perceptive observers such as Borromini and Piranesi (the latter knew imperial architecture in and near Rome as well as anyone has, until now) saw that surviving ancient structures often did not conform to Vitruvian and Renaissance formulations;[6] Alberti, of course, had wrestled with these contradictions, but his objectives were of a different order. Those who pointed to extremely varied and often unexpectedly ingenious design solutions had little success, for their ideas were drowned in a flood of Neo-classical dogma that in general devalued Roman architecture as the glories of Greek antiquity became better known. Durm sensed the truth, and was fascinated, as we are, by materials and methods of construction; his book is still important.[7] Noack was very acute; he saw a new architecture.[8] The rest of the story needs no rehearsal here, except to say that we now know that Roman experimental design is most often seen in two quintessentially imperial creations, bath buildings and great luxury villas, categories whose norms exist only in generalized functional definitions, not in architectural ones.

I am grateful for this opportunity to attempt to revise in some degree the traditional reading of the evidence. Using features of the Great Church as goals, certain Roman experiments fall into a kind of order, a tentative order, needless to say, but perhaps a useful one. The object is not to reflect on what is eastern or western within the Church, or to rehearse the path of the great pendentive hunt (surely Ward-Perkins, in his brilliant 1947 article, brought it nearly to a halt),[9] or to raise the old questions, again, about Anthemius's knowledge of Rome or the possible results of family members' residences there. It goes without saying that nothing said here will explain Anthemius's genius or the Church's incomparable architectural presence. But perhaps, by tracing the evolution of a few selected features, the Church's genealogy can be refined somewhat, and the unflagging continuity of Roman experimental design can be given a certain shape.

5 W. L. MacDonald, *The Architecture of the Roman Empire* (New Haven, Conn., 1986), 2: 3, 180, 186–7, 248.

6 F. Borromini, in his *Opus architectonicum* (reprint, Rome, 1965), 36; see also A. Blunt, *Borromini* (London, 1979), 38, 19, 70, 99, 116; and P. Portoghesi, *Borromini* (London, 1968), 6–9. On Piranesi see J. Wilton-Ely, *The Mind and Art of Piranesi* (London, 1978); K. Lehmann, "Piranesi as Interpreter of Roman Architecture," in *Piranesi* (Northampton, Mass., 1961), 88–98; and W. L. MacDonald, *Piranesi's Carceri: Sources of Invention* (Northampton, Mass., 1979).

7 J. Durm, *Die Baukunst der Etrusker: Die Baukunst der Römer* (Darmstadt, 1885).

8 F. Noack, *Die Baukunst der Altertums* (Berlin, 1910).

9 J. B. Ward-Perkins: "The Italian Element in Late Roman and Early Medieval Architecture," *Proceedings of the British Academy* 33 (1947), 163–94 (the pendentive hunt); idem, "Nero's Golden House," *Antiquity* 30 (1956), 209–19.

Roman architects relentlessly explored the possibilities inherent in square plans and the hypothetical cubes they imply. The results range from straightforward modular planning to very complex, almost baroque schemes wherein the square's cardinal and diagonal axes anchor satellite spaces symmetrically to the central space. By the late first century A.D. opposite sides of the cube sometimes vanish, replaced by reciprocal, expansive curving volumes; these, together with the cube itself, will be vaulted over. Pliny has such a room, containing cold plunges on either side of the central space,[10] and the motif is found in later baths and in *memoriae* as at Hippo and elsewhere.[11] It is the confrontation of the twin curves that explains the success of this kind of plan, for they immediately signal containment by forming a seamless yet symmetrical boundary; all floor-level angles have disappeared. It is from this concept, a central square and the cube it produces, that Anthemius generated his grand plan and unique elevation. Possibly he reflected on the Roman civil basilica with apses at both ends, but whatever his sources, his square and cube determine the positions and dimensions of almost all major design features of the building. That his cube hardly exists physically does not in any way invalidate its power; it is the same cube that invisibly encases the Pantheon or determines the central space of Saint Simeon Stylites, all such being cases of the Roman sense of interior space put to new purposes. The almost Euclidean clarity of the Great Church's theoretical main lines is not without precedent, though scale and the artistic handling of relationships among its chief interior features set the Church apart.

Once having determined the central core of his plan, Anthemius added arcaded niches to the broad hemicycles. In their placing they closely resemble that of innumerable diagonally located niches in Roman chambers often of square-and-half-circle plans. Building M at Side comes to mind, as do bath designs, villa pools, and so on. What may be less familiar is that curving arcades, so appropriate in the Great Church, were fairly common in Roman buildings, and not only in Late Antiquity, as at Santa Costanza. At Hadrian's Tivoli Villa they were very prominent, for example, in his Arcaded Triclinium, which began life as a somewhat imprecise square banquet chamber fronted by a large fountain room but was soon transformed by the addition of square-wide semicircular features to three sides (Figure 3).[12] Surviving two-way springers show that arcades rose from the curving colonnades; the roofing is uncertain. Thus, Anthemius built out from his central square – the tonic, to use a musical analogy, of his architectural composition – with diminishing but harmonic volumes, each visually and volumentrically dominated by the one from which it recedes, in what seems to me to be, in conception at least, a very Roman fashion. Volumetric dependency, a major key to high imperial design, was raised to new artistic levels in Justinianic architecture, where at times one is almost in the spatial world of Moslem *iwanat* even while under the spell of the last great phase of classical architecture.

Diagonal planning, combined with curved colonnades carrying arches, produced views suggesting partly obscured spaces in the manner of the stage designer's coulisses. These angled intimations, arched over and unresolved,

10 Pliny the Younger, *Letters* 2.11.7. 11 E. Marec, *Monuments chrétiens d'Hippone* (Paris, 1958).

12 H. Kähler, *Hadrian und seine Villa bei Tivoli* (Berlin, 1950); W. L. MacDonald and J. A. Pinto, *Hadrian's Villa* (forthcoming).

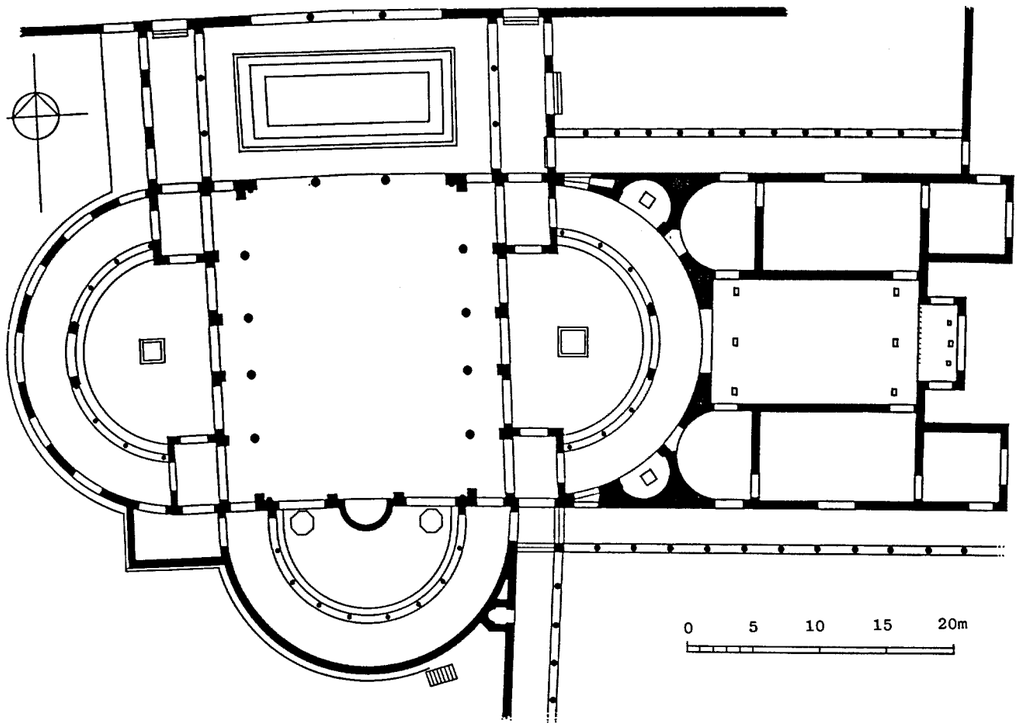


Fig. 3. The Arcaded Triclinium, Hadrian's Villa near Tivoli, A.D. 120s; plan.

are all the more effective because of the rational, orthogonal nature of the building's outer envelope within which they unfold. Few buildings contain grand architecture within architecture, and of those that do none I know of can compare with the Great Church. Hadrian, that great experimenter, managed it at the famous Island Enclosure at his Tivoli Villa, where he exploited curves and angled views successfully though all on one level, a moated island within a circular building. At the Great Church, up through two stories, the changes of view both within the aisles and galleries and out from them change almost endlessly; perhaps not even the lighting is more impressive. Because the opportunities inherent in the square's diagonals and the circle's radiuses so intrigued Roman designers, overlapping, coulisse-like views naturally followed. The so-called Temple of Minerva Medica (Figure 4) records this well and may mark the beginning of what it is difficult not to think of as artistically incommensurable, if not irrational, space of the kind that was a specialty of sixth-century architects – for example, those of San Vitale and Saints Sergius and Bacchus. It may be, as Ward-Perkins thought, that Severus's octagonal suite for Nero's palace, with its toed-in, intercommunicating chambers, first pointed architects in this direction.

Although mosaics lie somewhat outside the subject here, it should be said that important original developments in Roman planning are sometimes du-

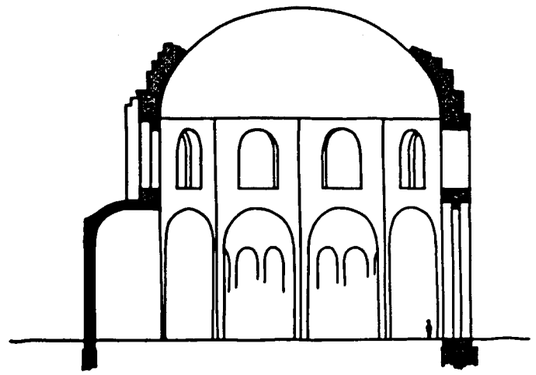


Fig. 4. The so-called Temple of Minerva Medica, Rome, early fourth century; section.

plicated in mosaic pavement patterns;[13] which came first is not yet clear, but the affinity between the two, often very close, is worth careful study. The extended circle, the octagon, the corner niches are all there, as are endless changes in the circle–square relationship. Examining mosaics for resemblances to architectural plans is very revealing in that the similarity of forms conceived by master mosaicists and major architects can be remarkable. Even flowing, reversing curves, of the kind seen in innovative Hadrianic architecture at Baiae and Tivoli, are common. The relevant pavements date chiefly from the second and third centuries, when Roman architects went from one innovation to another.

In order to get the interior effects he wanted, Anthemius removed some structural solids from our vision, either by placing them outside the building's orthogonal envelope (Figure 5) or by masking them by means of a kind of artistic sleight of hand; for each there was Roman precedent for the principles involved. Diocletian's Baths in Rome preserve a buttress system, for the groin-vaulted central hall, that closely resembles the one in Istanbul: The towers are split at the base longitudinally to form aislelike passages above whose roofs they rise externally to help support the main vault. On one exterior side, the northeast, they are used to divide the bays of a huge scenic wall facing the outdoor swimming pool, a good example of the Roman desire to make essential architectural features do double duty whenever possible. Such structural devices make very large wall openings possible as the windows at both the Baths of Caracalla and Diocletian record (Figure 6).[14] In this connection it is useful to recall the Baths of Zeuxippos, hard by the Hippodrome, which to judge by what evidence of the building we have would have supplied any Constantinopolitan architect with much useful information (Figure 7). If one seeks evidence of exteriorization of structure combined with angled

13 Relationships between these mosaic patterns and architectural planning are discussed in MacDonald and Pinto, *Hadrian's Villa*.

14 W. Müller-Weiner, *Bildlexikon zur Topographie Istanbuls* (Berlin, 1977), 51; C. Mango, *Le développement urbain de Constantinople (IVe–VIIe siècles)* (Paris, 1985), 26, 33, and *The Brazen House: A Study of the Vestibule of the Imperial Palace in Constantinople* (Copenhagen, 1959), 37–42.

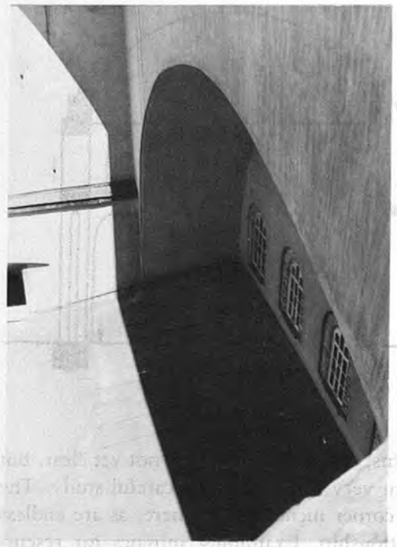


Fig. 5. The Great Church, Istanbul; the south superstructure arch, from above.

and arcuated views, both can be found at the Minerva Medica (Figure 8). How useful it would be to know what the hulks now standing at Tralles looked like in Anthemius's day.

As for the sleight of hand, it took two forms. One was to so relate major structural members as not to reveal their bulk, in contrast, say, to the vivid articulation of structure within the tabularium gallery; this is seen throughout the Great Church where arches meet vaults. The other method, dating back to the first century A.D., was to sheath the solids with sheets of marble, sometimes with mosaic. These techniques are so familiar that few examples need be given, but it is significant that across the empire much evidence for marble sheathing is preserved, including cases of matched or reversing veining, as for example at Hippo. For the student of imperial architecture, early Byzantine buildings contain much important information, not the least that of the effects imperial architects and craftsmen obtained from nonstructural marblework. An etching of the 1920s, showing a view across the Arcaded Triclinium at Hadrian's Villa, described earlier, gives a good sense of the reflective qualities of this technique: Some details are invented, but the effect of light on the marble pavement, seen in the foreground, is correct. And there is ample evidence, both textual and archaeological, of the use of gold in Roman painting and decorative metalwork.

The cavities within the building's fabric, both the utilitarian ones and those required by the design system as well as by otherwise overwhelming masses of masonry, reflect Roman practice.[15] Such cavities can be seen at several points in the ruins of the Baths of Caracalla at Rome, and they are common features of Hadrianic monumental design, as in the honorific arch at

15 K. J. Conant, "The First Dome of St. Sophia and Its Rebuilding," *Bulletin of the Byzantine Institute* 1 (1946), 71–8; R. J. Mainstone, *Hagia Sophia: Architecture, Structure and Liturgy of Justinian's Great Church* (London, 1988), chap. 8.

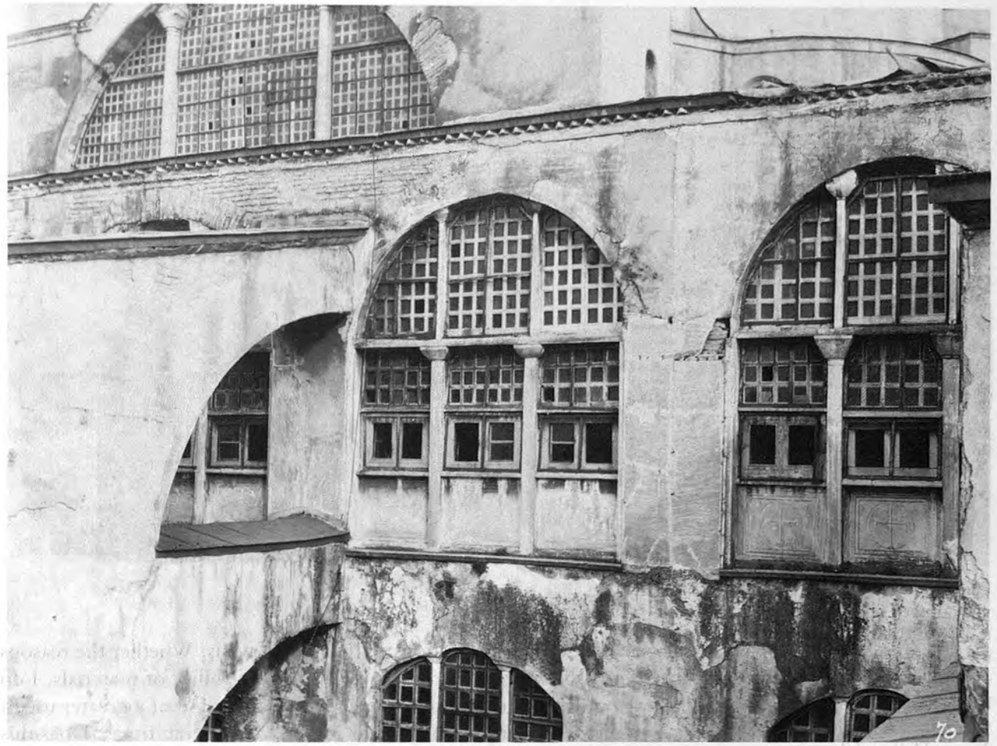


Fig. 6. The Great Church; west facade windows.

Antinoöpolis[16] or within the sophisticated structure of the Pantheon. The Scenic Triclinium at Hadrian's Villa, well preserved except for the huge transverse barrel vault that once faced the still-standing fabric, is riddled with radially set-out chambers on three levels. This much misunderstood building also preserves evidence for disguised structural junctions of the kind just mentioned. The work is less subtle than at the Great Church, but the principle seems to be the same: Surface, and lines of junction, take precedence over any overt assertions of structural bulk.

But the most Roman feature of the Church's fabric is the nearly volumetric equality of its terra-cotta tiles and their mortar bedding (Figure 9). Anyone who has excavated Roman imperial brickwork knows how tenacious the bond is between the two substances. The carefully fired brick, thoroughly cured, desert-dry and porous, takes to the mortar ardently. When carefully laid up from materials properly prepared, the resulting structure is as nearly indestructible as can be. In general, mortar joints are thinnest in the first century A.D., and although it would not be correct to say that they gradually thicken as time passes, it is true that there is much evidence of thickening in the third

16 Jomard's plates 57 and 58 (Antinoë) in vol. 4 of *La déscription de l'Egypte* (1817, plates reprinted 1987).

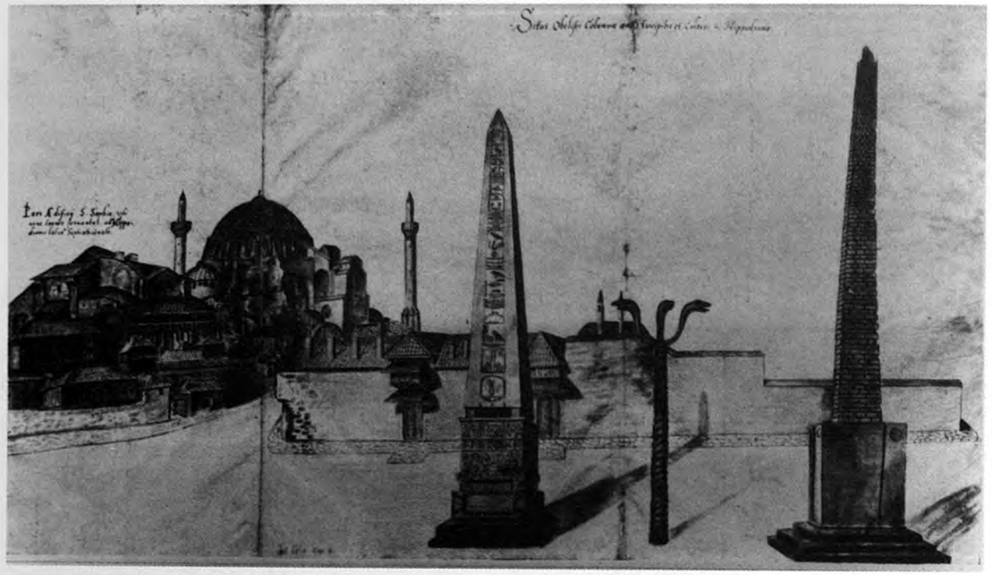


Fig. 7. Sixteenth-century view of the Hippodrome and the Great Church; the building at the left has all the earmarks of a Roman imperial bath – that of Zeuxippos? (From the Freshfield Album, Trinity College Library, p. 45, ms.0.17.2)

century, as for example in portions of the Nicaea walls. Whether the reasons for this were economic, or had to do with the availability of materials, I do not know, but there is evidence of change in the direction of a greater use of mortar all across the empire, beginning roughly in Severan times. Does this process, which might be said to culminate in the construction of the Great Church, mean that architects and builders found that they could in effect make concrete out of bricks and mortar, that they might have thought of their tiles as a form of aggregate? The thickness of the mortar joints at the Church (Figure 10) shows beyond doubt that Anthemius and his people regarded mortar as a structural material with at least the strength of brick, and this suggests, to me at least, that they gave much thought to concrete and its behavior. Even if these speculations are incorrect, the Church does reflect late Roman practice in the laying up of bricks.

Fascinating questions remain. What was the state of knowledge of applied mathematics in the sixth century? Could an expert today find evidence in the Great Church of some use of the newly developed algebra set out by Diophantus of Alexandria in the late third century?[17] He deals with equations of two or more variables, with solutions stated in whole numbers. Anyone with Anthemius's knowledge of mathematics, who was able to design and see built as complex and original a structure as the Great Church, has to be suspected of having made use of his knowledge in that enterprise. What is he likely to have known, and what practical applications might follow from that knowledge? In the history of ancient and early medieval architecture, such

17 T. Heath, *A History of Greek Mathematics* (reprint, New York, 1981), chap. 20; J. Klein, *Greek Mathematical Thought and the Origins of Algebra*. (Cambridge, Mass., 1968), chap. 10.

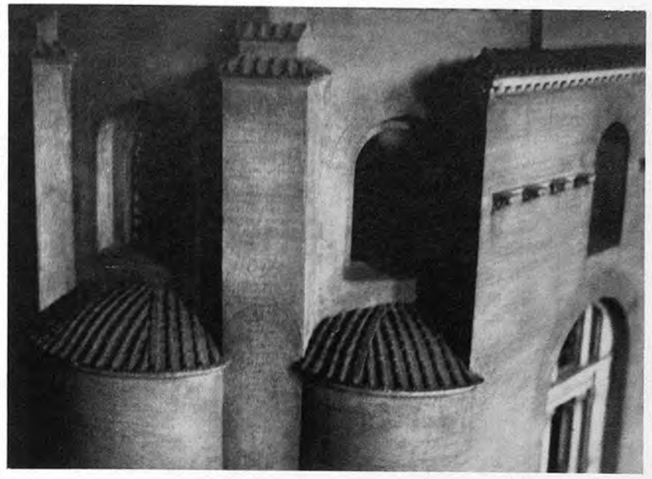


Fig. 8. The so-called Temple of Minerva Medica; detail of the model in the E. U. R. Museo della Civilta Romana, Rome.

topics sorely need attention. Then there is the matter of tradition, not only of the Roman ruler as a great builder, but of his association with the leading architect or architects of the day. Whether or not they were aware of it, tradition pushed Justinian and Anthemius forward. Mentalities, in spite of our French friends' remarkable efforts, are hard to recover, but one facet of the overall explanation of the Great Church must lie in the grand imperial tradition of which Justinian made so much, of which he was so conscious.

The Roman connection is written into the fabric of the building in the brickstamps, in the processional axis, with its telescoping apsidal conclusion, derived from earlier emperors' audience halls, and in the spreading vaults. That none of this appears to be Roman is not surprising; the Roman elements have been rethought, absorbed into a new vision. The ancestral lines have to be sought, I think, topically, except for one fundamental thing. The Church is a major, urban capitoline monument, the natural vehicle of the imperial message because of its location, size, and unrivaled interior space. Its Roman inheritance rests as much in its experimental quality as in any tangible forms, and it is this that gives it its assertively unique quality. The building loses nothing by being studied as a repository of certain Roman ideas and tendencies, because these appear in it only in their sixth-century forms, as the servants of a larger idea.

The number of basic design elements used by Roman architects was surprisingly small. But Euclidean figures and solids are rich with possibilities, as Euclid was at pains to point out, and by the second century A.D. confidence in structural techniques also encouraged experiment. By the sixties of the previous century Nero's famous eight-sided dome had been built, and the continuous-surface pendentive dome appears at least by the later second century, as at Gerasa. A vault of approximately ellipsoidal form, with continuous-surface pendentives, exists at Minori over an oblong room, and Hadrian's half-dozen scalloped vaults are well known (Baiae, the Horti Sallustiani in Rome, the Villa). That here and there examples of very unclassical design

Fig. 9. The Great Church; detail of the west facade brickwork.

solutions survive shows that innovation was on the minds of architects other than those of the court; these include perspective staircases (Minori, narrowing with the rise; Hadrian's Villa, the opposite), oval chambers (baths at Aachen and Ostia), true sinuous walls in the Jeffersonian manner (the Villa), conical solids (Ariccia), and truly baroque compositions as at Santa Maria Capua Vetere (the tomb called La Conocchia), and wall paintings (Apollo and the morning and evening stars, in the House of Apollo at Pompeii). And a host of very untraditional decorative forms survive also, of which the flower capital in the House of the Stags at Herculaneum and the reverse-curve capitals (*litus*-shaped) at Hadrian's Villa are representative examples.

More interesting are Great Church features apparently not prefigured in Roman times – for example, the direct attachment of a semidome to an arch of a pendentive block. The cold plunge suite in the Smaller Baths at Hadrian's Villa, however, implies this arrangement. The vaults there, by very good fortune, survive almost complete: Semidomed apsidal forms, extended by barrel vaults, join the main, groin-vaulted space, facing each other. But although Anthemius and Isidorus repeatedly pass beyond the existing repertory of design solutions, the fact that they did so places them firmly in the Roman experimental tradition. Perhaps the most significant thing about that tradition is that it runs counter to the view generally held about the nature of Roman imperial architecture. As long as the Maison Carrée and its like are seen as fully representative of Roman architecture, as long as Roman towns are said to be simply duplicates of a simple, grid-based model, the record of Roman experiment is bound to be kept in the shade. But the great Roman one-ended temple, a primary image in Western architecture if ever there was one, was rarely built after the erection of the Temple of Antoninus and Faustina in the Forum, and Roman towns, though conceptually related, were quite varied in

Fig. 10. The Great Church; detail of the superstructure brickwork.

their design; the last major grid dates from A.D. 100. From the perspective that a survey of Roman experimental design may provide, the Great Church is to some degree revealed as the natural, if transcendent, result.[18]

18 On the Great Church, see also W. R. Zaloziecky, *Die Sophienkirche in Konstinopel* (Rome, 1936); R. L. Van Nice, *St. Sophia in Istanbul: An Architectural Survey*, vol. 1 (Washington, D.C., 1965), vol. 2 (Washington, D.C., 1988); The Rome connection: E. H. Swift, *Hagia Sophia* (New York, 1940), 26, and the chapter entitled "Principles of Design."

DESIGN AND STRUCTURAL INNOVATION IN BYZANTINE ARCHITECTURE BEFORE HAGIA SOPHIA

SLOBODAN ĆURČIĆ

The building of the church of Hagia Sophia from 532 to 537 is generally viewed as an event of seminal importance for the history of Byzantine architecture.[1] Owing to its enormous size alone, the Great Church *was* a singular achievement. Nonetheless, scholarly assessment of the building has been prone to exaggeration. Its architects, Anthemius of Tralles and Isidore of Miletus, have been viewed as geniuses who, without much previous experience and without major precedents, created this architectural and engineering masterpiece. In recent times this point of view has slowly undergone modification.[2] Archaeological discoveries, such as that of the Hagios Polyeuktos, the second largest church in Constantinople, built between 524 and 527, have provided invaluable information for the theoretical reconstruction of design developments about which we know precious little.[3] The purpose of this essay is to expand our understanding of the architectural contribution of the fifth and early sixth centuries by examining what I believe to be certain instrumental steps leading toward the creation of Hagia Sophia.

The general inclination has been to view the architecture of the fifth century as quantitatively voluminous, geographically widespread, and – from the design point of view – standardized.[4] The creative component, though unquestionably present, would seem to have been drowned out by the vast volume of "standardized" construction. Basilican churches such as the Acheiropoietos, built around 450 in Thessaloniki, and Saint John in the famous Studios Monastery in Constantinople, begun in the 450s, illustrate the point.[5] By contrast, the period of architectural production during the age of Emperor Justinian I (527–65), the crowning achievement of which is the church of Hagia Sophia, has been viewed as one of great experimentation and creative fervor. These notions on the whole remain valid, and I do not intend to challenge them as such. What I hope to show is that certain structural and design principles were recognized and developed in the course of the fifth and the early sixth centuries. It is these developments, I would argue, that paved the way for the genesis of the Hagia Sophia. The Great Church, in other words, did *not* emerge ex nihilo. For all its greatness, for all the inventiveness and ingenuity of its architects, Hagia Sophia, as might be rationally expected in the preindustrial era, depended heavily on the cumulative process of design and technical experience.

Let me begin by examining first some of the qualities of what has been labeled "standard" architecture of the fifth century. The conservative trend in fifth-century architecture manifested itself in a variety of ways, but above all in the realm of structural solutions. The reduced scale of buildings, smaller spans, thicker walls, and less problematic roofing or vaulting schemes were all hallmarks of structural conservatism. Inasmuch as structural conservatism is a general characteristic of much preindustrial architecture, a particular manifestation sets this period apart from other conservative eras. The phenomenon, especially apparent in the fifth and sixth centuries, is the extensive reliance on the cross as an apotropaic symbol. By the fifth century, the cross had become a universal symbol of Christian victory.[6] Its use as such, as well as its generic decorative application in church architecture, must be distinguished from its clearly apotropaic role. As a protective device, the cross was used visibly near building openings such as doors and windows. A more significant, and, I would argue, apotropaic, *structural* role of the cross is encountered in numerous buildings where it was not necessarily meant to be visible. Two striking examples of such use come from the church of Saint John Studios in Constantinople, from the 450s, and from the church of Hagios Titos at Gortyna, on the island of Crete, probably dating from the end of the sixth century (Figures 11 and 12).[7] In both of these instances the cross appears on a spandrel between two arches, and would have been covered by marble revetment in the former case and by mosaic, fresco, or some other form of wall decoration in the latter case. The church at Gortyna reveals yet another structural application of a cross – on the keystone of an arch and apse vault in the north lateral chapel flanking the sanctuary. One cannot argue

1 R. Mainstone, *Hagia Sophia: Architecture, Structure and Liturgy of Justinian's Great Church* (London, 1988), is but the latest in a series of monographic studies on Hagia Sophia that have appeared over the past century. This work includes an up-to-date selected bibliography, as well as certain relevant historiographical insights. See also R. Krautheimer, *Early Christian and Byzantine Architecture,* 4th ed., rev. by R. Krautheimer and S. Ćurčić (Harmondsworth, 1986), chap. 9.

2 R. Mark, *Light, Wind, and Structure: The Mystery of the Master Builders* (Cambridge, Mass., 1990), 74–89, offers a concise historiographical assessment of this issue.

3 M. Harrison, *A Temple for Byzantium: The Discovery and Excavation of Annicia Juliana's Palace-Church in Istanbul* (Austin, Tex., 1989), esp. chap. 4.

4 For the articulation of this point of view, shared by many authors, see Krautheimer, *Early Christian and Byzantine Architecture:* "The inventiveness and experimentation of the Constantinian age gives way to the establishment of norms, and distinct building types, which had gradually evolved for different liturgical functions, rapidly become standardized" (94).

5 C. Mango, *Byzantine Architecture* (New York, 1985), 39 and fig. 46 for the former; 38–9 and fig. 43 for the latter.

6 H. R. Storch, "The Trophy and the Cross: Pagan and Christian Symbolism in the Fourth and Fifth Centuries," *Byzantion* 40 (1970), 105–17.

7 T. F. Mathews, *The Byzantine Churches of Istanbul: A Photograph Survey* (University Park, Pa., 1976), figs. 15–25 (St. John Studios). The church of Hagios Titos at Gortyna lacks a comprehensive publication; A. K. Orlandos, "Neoterai erevnai en Hag. Tito tes Gortynes," *Epetiris Hetaireias ton Byzantinon Spoudon* 3 (1926), 301–28, is still basic. To these one should add a related early example from the Octagon in the Palace of Gallerius in Thessaloniki. Executed in brick, within a circle of radially laid bricks, the cross in the main apse of the Octagon was intended to be covered with marble revetment and therefore rendered invisible; see N. C. Moutsopoulos, "Contribution à l'étude du plan de ville de Thessalonique à l'époque Romaine," in *Atti del XVI Congresso dell architettura* (Rome, 1977), 238–9.

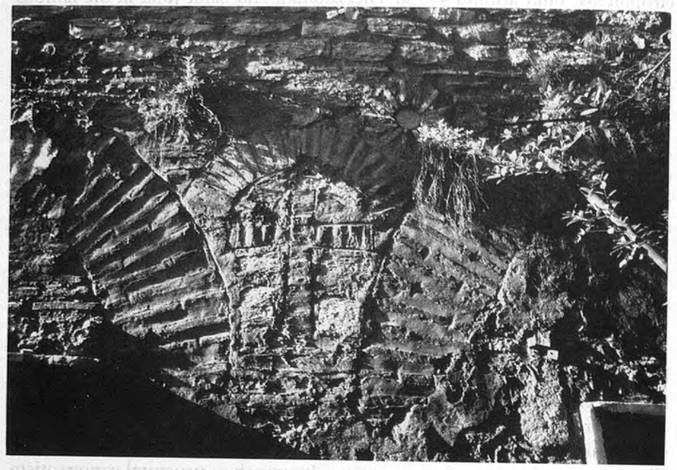


Fig. 11. St. John Studios, Istanbul; north wall, interior detail. (Photo: author)

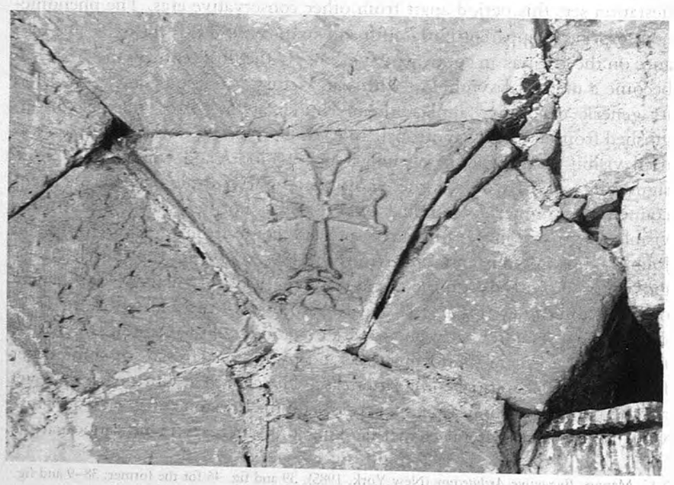


Fig. 12. Hagios Titos, Gortyna; main apse window, detail. (Photo: author)

with absolute certainty whether this particular cross would have been visible. A comparable cross on the springer of the two arches forming the narthex porch of the fifth-century Church 31 at Binbir Kilise would certainly have been visible, as is apparent from the remnants of red paint in the background of the rondel containing the cross (Figure 13).[8] A distinctive, though related

8 W. M. Ramsey and G. L. Bell, *The Thousand and One Churches* (London, 1909), fig. 126 (Church 31, narthex porch).

Fig. 13. Church 31, Binbir Kilise; narthex porch. (Photo: D. Winfield)

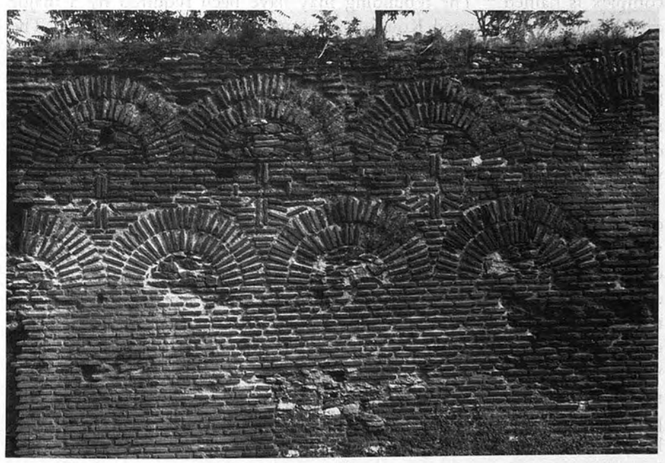


Fig. 14. City walls, Thessaloniki; western stretch, detail. (Photo: author)

group of apotropaic brick crosses may be seen on a Western stretch of the fifth-century city walls of Thessaloniki (Figure 14).[9] I suggest that these crosses, along with the multiple brick arches that surround them, would have had the function of ensuring the structural stability of the wall itself. In fact, all of the crosses shown, appearing as they do at salient structural points – on span-

9 The city walls of Thessaloniki deserve serious historical and architectural study. The most thorough, up-to-date study remains O. Tafrali, *Topographie de Thessalonique* (Paris, 1913), chaps. 2 and 3, esp. 75, regarding the crosses in question, though these are not illustrated.

Fig. 15. Eustolios complex, Kourion; floor mosaic inscription. (Photo: author)

drels, keystones, or springers – illustrate reliance on the miraculous power of the cross to ensure the structural stability of the building, in all likelihood against earthquakes.

Confirmation of this hypothesis, I believe, comes from a floor mosaic inscription excavated within the so-called Eustolios complex at Kourion on Cyprus (Figure 15). The inscription, dating from around 400, belongs to a major rebuilding campaign underwritten by one Eustolios, for whom the complex is named.[10] The rebuilding may have been required by a major earthquake that devastated Kourion sometime between 365 and 372. The translation of the inscription, as recently published by Eunice and Henry Maguire, reads as follows: "Not by big stones, not by firm iron and tawny bronze, and not even by steel are these buildings girded, but, by the much-invoked signs of Christ."[11] The tenor of this inscription suggests a clear lack of confidence in current structural practices – a lack of confidence caused, as would be understandable, by the earthquake in question.

Recent excavations in Kourion have revealed the devastating effect of this earthquake.[12] Excavations elsewhere on Cyprus have brought to light other ways of coping with what appear to have been recurring major earthquakes on the island. The foundation walls of a small fifth-century basilica at Polis excavated in 1984–8 by the Princeton Department of Art and Archaeology team have revealed multiple rebuildings, each characterized by the addition of a layer of masonry (Figure 16).[13] The outcome, as illustrated by the spur wall of the original southern nave arcade, was a quadrupling of the original masonry thickness, resulting in an amorphous, 2-m-thick wall mass in the place of what was initially a 50-cm-thick wall spur (Figure 17). In another location in the same building we found a cross within a circle, crudely incised into plaster just above the pavement (Figure 18). The cross must have been incised in the still-wet plaster by a workman responsible for one of the re-

10 H. W. Swiny, ed., *An Archaeological Guide to the Ancient Kourion Area and the Akrotiri Peninsula* (Nicosia, 1982), 132–9.

11 E. D. Maguire, H. P. Maguire, and M. J. Duncan-Flowers, *Art and Holy Powers in the Early Christian House* (Urbana, Ill., 1989), 19 and fig. 18.

12 D. Soren, "An Earthquake on Cyprus: New Discoveries from Kourion," *Archaeology* 38, no. 2 (1985), 52–9.

13 For a brief preliminary report see S. Ćurčić, "An Early Byzantine Basilica at Polis, Cyprus," in *17th International Byzantine Congress: Abstracts of Short Papers* (Washington, D.C, 1986), 87–8.

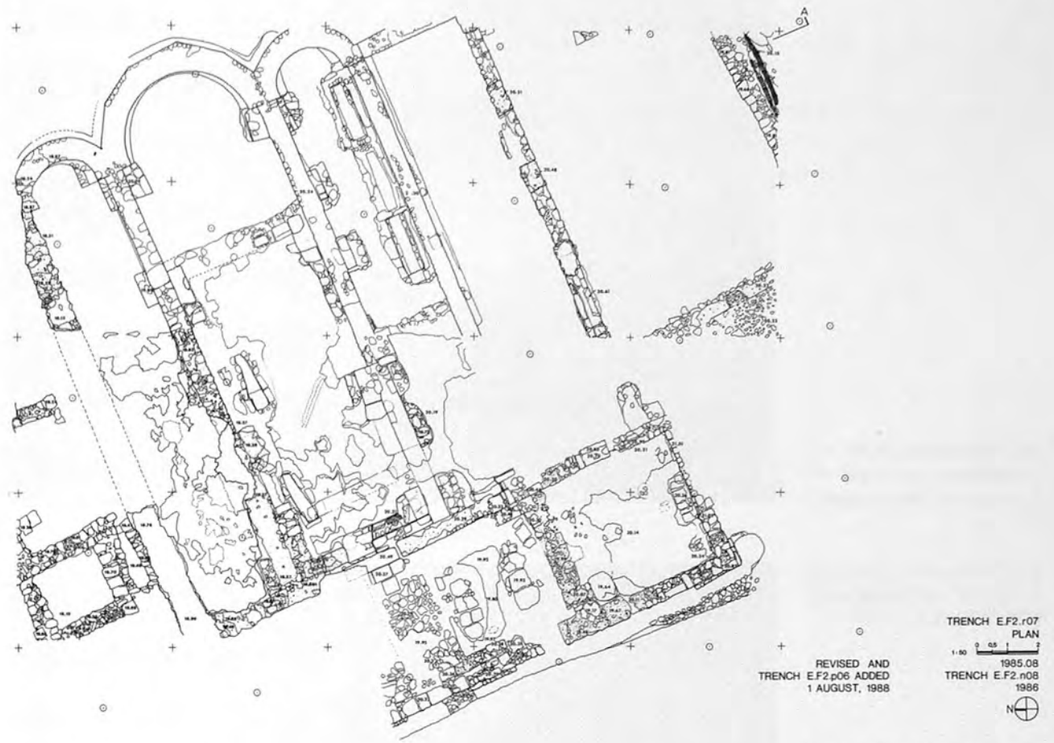


Fig. 16. Basilica, Polis; plan. (From Princeton University Archaeological Expedition)

building phases of the church. It would appear that it was placed there as a form of "reinforcement," adding a magic "force" to the layer of masonry, whose structural contribution could not be counted on.

It should be noted that thickening of masonry as a structural means of solving earthquake problems apparently became the architectural norm in Cyprus during the following centuries. In fact, one could argue that a distinctive, regional style of architecture evolved as a by-product of such structural interventions. Medieval churches of Cyprus are generally characterized by an organic quality of seemingly heaped-up masonry walls, smooth, undulating roof lines, relatively low profiled domes, and small windows.[14] These aesthetic qualities were frequently arrived at over a period of time as a result of many rebuildings and building reinforcements, as is the case with the churches of Panagia Angelokistos at Kiti (Figure 19) and the Panagia Khryseleusa at Emba.[15] The same aesthetic preference appears in churches designed and built in a single campaign, as in the two twelfth-century examples – the Hagioi

14 A. H. S. Megaw, "Byzantine Architecture and Decoration in Cyprus: Metropolitan or Provincial?" *Dumbarton Oaks Papers* 28 (1974), 59–88, which discusses various idiosyncrasies of Cypriot architecture from Late Antiquity to the Middle Ages.

15 Architectural studies of the churches at Kiti and Emba are lacking; for brief comments see A. Stylianou and J. A. Stylianou, *The Painted Churches of Cyprus* (London, 1985), 49–50 (Kiti) and 409 (Emba). See also G. A. Sotiriou, *Ta byzantina mnēmeia tēs Kyprou* (Athens, 1935), fig. 16 (plan and section of Kiti) and fig. 27 (plan and section of Emba).

Fig. 17. Basilica, Polis; southwest nave corner, foundations. (Photo: author)

Fig. 18. Basilica, Polis; south nave wall, foundation detail. (Photo: author)

Apostoloi at Perachorio (Figure 20) and the Hagios Theodoros at Sotira, of which only the ruined narthex remains standing.[16]

Structural conservatism noted in these cypriote solutions was not restricted

16 For Perachorio see A. H. S. Megaw and J. W. Hawkins, "The Church of the Holy Apostles at Perachorio, Cyprus, and Its Frescoes," *Dumbarton Oaks Papers* 16 (1963), esp. 280–4. To my knowledge the plan of the church of Hagios Theodoros at Sotira is unpublished. For a photograph of Hagios Theodoros, see Sotiriou, *Ta byzantina mnēmeia*, pl. 27 (bottom).

Fig. 19. Panagia Angelokistos, Kiti; from northeast. (Photo: author)

Fig. 20. Hagioi Apostoloi, Perachorio. (Photo: author)

to provincial environments deprived of any realistic possibility of structural experimentation. Even in the capital of the Byzantine Empire, related indications of this conservatism were apparent in the course of the fifth and early sixth centuries. The church of Hagios Polyeuktos, mentioned earlier, illustrates this point (Figure 21). This large church was evidently designed as a domed basilica. Because only the foundations of the building survive, we can hypothesize that the nave was barrel-vaulted and that it had a dome over its middle section, and thereby would have differed from "standard" basilican

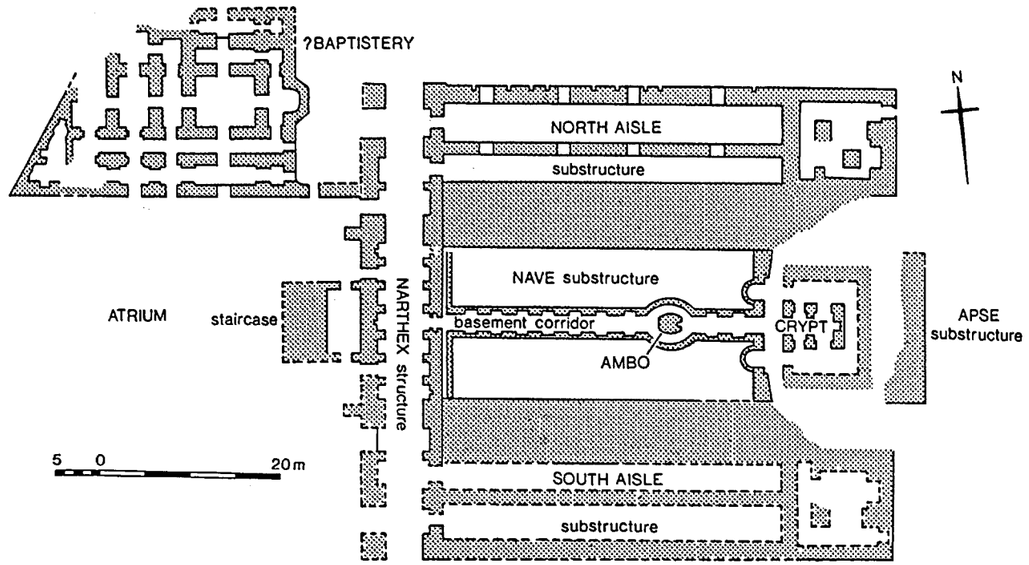


Fig. 21. Hagios Polyeuktos, Istanbul; plan. (From M. Harrison)

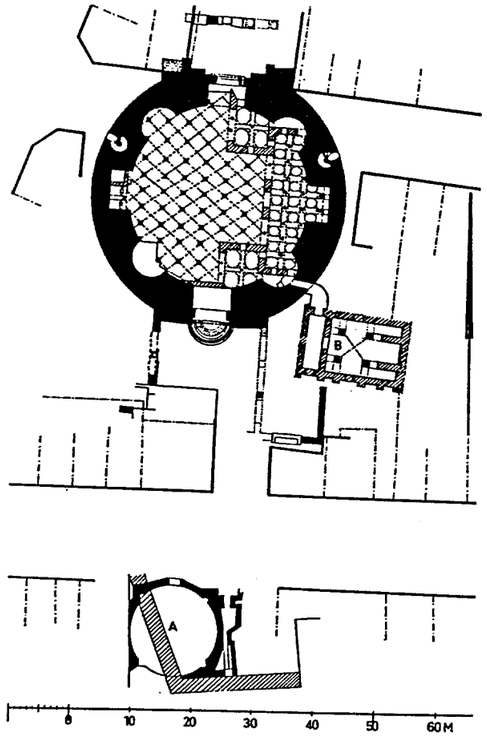


Fig. 22. Myrelaion Rotunda, Istanbul; plan. (From W. Müller-Wiener)

churches of the fifth century. The presence of vaulting, which could be considered a design "innovation," can be deduced from its massive foundations. The conservative aspects of its structural solution are made manifest in two distinct ways. First, the building, although apparently domed, displays a basilican layout of the foundation walls. In other words, the two parallel walls seem to be more in keeping with the tradition of basilican planning than with the presence of a new structural component – the dome – whose structural behavior might have merited a different solution within the foundations. Second, the thickness of the two main foundation walls – nearly 7 m – suggests a gross exaggeration of practical need. These foundation walls of unprecedented thickness were evidently overdesigned in the hope of preempting problems such as the effects of earthquakes.[17] Judging by the surviving evidence, this was an erroneous approach, for the building appears not to have survived beyond the end of the twelfth century.[18]

Another large building in Istanbul whose remains were revealed through excavations displays an identical brand of structural conservatism and, it seems, with comparable end results. Relatively little is known about this enormous round structure, with a 29.6-m interior and 41.8-m exterior diameter (Figure 22). Identified as the "Myrelaion Rotunda," it is believed to have been a component of a fifth-century palace complex.[19] In terms of its general architectural character, the building must have belonged to the Late Antique progeny of the Pantheon in Rome.[20] In fact, it would seem to have been one of the largest and one of the youngest of this distinctive family of buildings. Though its design appears to have followed the Pantheon model closely, the thickness of its wall (6.1m) seems proportionally much too great compared with that of the Pantheon (6.4-m wall thickness; 43.3-m interior diameter). As was the case with Hagios Polyeuktos, the builders of the Myrelaion Rotunda appear to have opted for a conservative structural approach, wary, as they must have been, of earthquakes in Constantinople.

At this point it is necessary to resist the temptation to view *all* of the Constantinopolitan builders before ca. 530 as structural "conservatives." We will now turn to a number of other structural solutions that, I hope, will demonstrate that in fifth-century Constantinople structural experimentation coexisted with structurally cautious, more conservative design approaches. The structural solution employed for the first dome of Hagia Sophia is but the final product of this experimental spirit. Its design presupposes the articulation of certain sophisticated structural principles that, I will argue, were mastered through extensive experimentation carried out in the course of the fifth century.

17 Harrison, *A Temple of Byzantium*, 52–3, figs. 47 and 48.

18 Ibid., 142. W. Müller-Wiener, *Bildlexikon zur Topographie Istanbuls* (Tübingen, 1977), 190–1, by contrast, suggests that the building may have been destroyed much earlier, possibly even in the great earthquake of 1010.

19 Müller-Wiener, *Bildlexikon*, 240–1 and fig. 85 (106).

20 R. Naumann, "Der antike Rundbau beim Myrelaion und der Palast Romanos I Lakapenos," *Istanbuler Mitteilungen* 16 (1966), 199–216. J. J. Rasch, "Die Kuppel in der römischen Architektur, Entwicklung, Formgebung, Konstruktion," *Architectura* 15, no. 2 (1985), 117–39, is an important study of Roman domed buildings, but it considers only those examples in which the vaulting is still in place. As a consequence, several major buildings that were undoubtedly domed (including the Myrelaion Rotunda) are not mentioned at all.

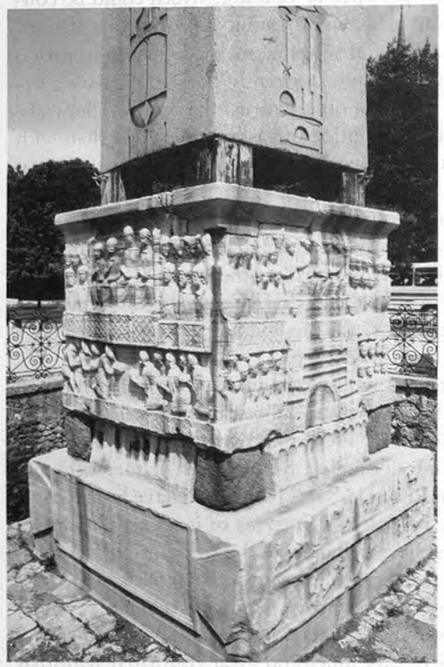


Fig. 23. Obelisk of Theodosius I, Istanbul; base. (Photo: author)

Principle 1: The Four-Point Support

The four-point support is one of the most fundamental structural principles[21] whose application affected a wide range of Byzantine buildings, from utilitarian structures such as cisterns, to churches, and even to a curious engineering solution employed in the base of the Obelisk of Theodosius in Constantinople (Figure 23).[22] The principle was known to the Roman architects who

21 For an extensive theoretical discussion of the origins and development of this principle see H. Sedlemayr, "Das erste mittelalterliche Architektursystem," *Kunstwissenschaftliche Forschungen* 2 (1933), 25–62 (reprinted in H. Sedlmayr, *Epochen und Werke: Gesammelte Schriften zur Kunstgeschichte* (Vienna, 1959), 1: 80–139), and idem, "Zur Geschichte des justinianischen Architektursystems," *Byzantinische Zeitschrift* 35 (1935), 38–69.

22 The 60-ft-high red-granite obelisk, brought from Karnak in Egypt, was erected in 390 on the *spina* of the Hippodrome under the auspices of the city prefect, Proculus, and in commemoration of a triumph of Theodosius I. The obelisk rests on a monolithic cubical marble base, the faces of which were decorated with well-known reliefs depicting Emperor Theodosius and members of his court in various Hippodrome-related ceremonies. The obelisk itself does not sit directly on this marble pedestal, but is slightly elevated on four solid bronze cubes aligned with its four corners. This somewhat precarious-looking arrangement ensures that overturning forces are carried at the exterior of the obelisk base for maximum stability. Even in a city as ravaged by earthquakes as is Istanbul, the obelisk has remained erect for 1,600 years. As such, it is one of the three monuments from the fourth century still standing in Istanbul. See G. Bruns, *Der Obelisk und seine Basis auf dem Hippodrome zu Konstantinopel*, Istanbuler Forschungen, 7 (Istanbul, 1935), esp. 15 (and figs. 21–4), on the bronze cubes, and 83–4, on various technical aspects of the obelisk support. Also, H. Wrede, "Zur Errichtung des Theodosiusobelisken in Istanbul," *Istanbuler Mitteilungen*, 16 (1966), 178–98.

employed it in conjunction with cross-vaults or groin vaults and invariably relied on piers as its four-corner supports. Owing to the thinner structural shells and lighter materials that they used, Byzantine builders were able to support their vaulting units on slenderer corner elements, frequently on columns instead of piers.

The four-point support system may be perceived as having had a nonstructural avenue of development from Roman quadrifrons (tetrapylon) triumphal arches. The symbolic nature of quadrifrons arches was preserved in Byzantium, translated, as it were, from pagan into Christian usage. At the beginning of this development stood the famous Milion, a domed quadrifrons arch erected in Constantinople during the first half of the fourth century.[23] An apparently identical formula was employed at roughly the same time at Ephesos, but for a distinctly Christian purpose – to mark the shrine of St. John the Evangelist.[24] The close relationship between the pagan quadrifrons arch and Byzantine church architecture took on different forms, as is attested to by archaeological evidence and by written sources.[25] The same scheme undoubtedly stood in the background of the development of a distinctive group of late-fourth- and fifth-century churches, labeled "aisled tetraconchs."[26] At least one church of this group, the East Cathedral of Apamea in Syria, built after 400, was evidently domed.[27] Its central, square bay is marked by four massive masonry piers, which in all likelihood were intended to sustain a dome. Two later monuments of the same group – the so-called Red Church at Perushtitsa, Bulgaria (ca. 500?), and the no longer extant sixth-century Hagia Sophia at Adrianople (Edirne, Turkey) – were either built with the intention to, or subsequently modified to, support a dome.[28]

23 Müller-Wiener, *Bildlexikon*, 216–18. The Milion was situated at the end of the Mese, the main street of Constantinople, and it functioned as the official milestone from which the distances of other cities in the Empire were measured.

24 J. Keil, *Die Johanneskirche*, Forschungen in Ephesos, 4, pt. 4 (Vienna, 1951), 224–7.

25 The former case is illustrated by the recently discovered, presumably monastic triconch church (fifth or tenth to eleventh century) at Aphrodisias, whose main structural piers were reused portions of an ancient tetrakionon that marked the intersection of two streets; see R. Cormack, "The Classical Tradition in the Byzantine Provincial City: The Evidence of Thessaloniki and Aphrodisias," *Byzantium and the Classical Tradition*, ed. M. Mullett and R. Scott (Birmingham, 1981), esp. 114–16. A seventh-century (?) church dedicated to the Forty Martyrs of Sebaste was either within or near the "bronze" tetrapylon of the same name in Constantinople. Completely destroyed sometime after 1420, this tetrapylon is known only from written sources; see C. Mango, *The Art of the Byzantine Empire, 312–1453: Sources and Documents* (Englewood Cliffs, N.J., 1972), 130; G. P. Majeska, *Russian Travelers to Constantinople in the Fourteenth and Fifteenth Centuries*, Dumbarton Oaks Studies, 19 (Washington, D.C., 1984), 230–1.

26 W. E. Kleinbauer, "The Origin and Functions of the Aisled Tetraconch Churches in Syria and Northern Mesopotamia," *Dumbarton Oaks Papers* 27 (1973), 91–114; idem "The Double-Shell Tetraconch Building at Perge in Pamphylia and the Origin of the Architectural Genus," *Dumbarton Oaks Papers* 41 (1987), 277–93.

27 J. C. Balty, *Guide d'Apamée* (Brussels, 1981), 105–20, esp. 105–6.

28 A. Frolow, "L'Eglise Rouge de Peruštica," *Bulletin of the Byzantine Institute* 1 (1946), 15–42; D. Panaiotova, *Chervenata tsurkva pri Perushtitsa: Opit za restavratsiia* (Sofia, 1956). For Adrianople see N. Mavrodinov, "L'origine de la construction et du plan de Sainte-Sophie à Constantinople," in *Actes du VI Congrès international d'études byzantines* (Paris, 1951), 2: 277–98, esp. 286–93, and figs. 6–8.

Principle 2: Pendentive Dome Geometry

Byzantine architects are generally given credit, if not for the invention, then certainly for the proliferation, of the domical vault and the so-called pendentive dome. The geometry of a pendentive dome, by definition, is derived from a hemisphere from whose sides four identical segments are sliced off so as to leave a square base (Figures 24 and 28c).[29] The top remaining segment of this sphere, whose circular base is tangential to the apexes of the four arches, is defined as a *pendentive dome;* the four remaining triangular sections of the sphere are referred to as *pendentives*. Each of the pendentives tapers downward to a theoretical point, defining the four-point support system. A superb contemporary three-dimensional model of such a system is illustrated by the shrine or reliquary, dated ca. 500, now in the Treasury of San Marco in Venice (Figure 25).[30] This ciborium can be understood as the "ideal version" of the structural system we are attempting to define. It utilizes both principles we have referred to thus far: first, the principle of four-point support, as defined by the four columns; and second, the principle of the pendentive dome, resting on a square base.

The first dome of Hagia Sophia is generally understood to have been based on precisely the same principle I have just outlined.[31] It has been thought of as the first monumental attempt to employ a pendentive dome, and possibly even the first attempt to use such geometry altogether. In the light of our current knowledge of Constantinopolitan architecture both notions require careful reassessment. Unfortunately, the surviving foundations of the Hagios Polyeuktos offer no useful information on the nature of its dome or the system of its supports. Owing to its size, one presumes that, like Hagia Sophia, it had a a dome supported on four massive piers.[32] More promising information may be derived from the geometry of a medium-sized rotunda excavated in the immediate vicinity of the great Myrelaion Rotunda in Istanbul (Figure 22). This structure, apparently contemporary with the great Rotunda, has been totally ignored by Byzantine architectural historians. First published by David Talbot Rice, its plan has been reproduced on a number of occasions, but beyond that it has not received more than passing notice (Figure 26).[33] Though considerably smaller than its giant neighbor, it was a fairly sizable building, measuring ca. 15 m in diameter, just less than one-half the diameter

29 The question of the origins of pendentive domes has long preoccupied architectural historians. Suffice it to mention but a few: E. Langlotz, "Zur Entstehung der Pandantif-Kuppel," in *Festschrift für Carl Weickert,* ed. G. Bruns (Berlin, 1955), 35–40; R. M. Harrison, "Churches and Chapels of Central Lycia," *Anatolian Studies* 13 (1963), 117–51; and most recently Rasch, "Die Kuppel," 126 and n. 63, and 129, nn. 73–5, who wisely leaves the question open.

30 D. Gaborit-Chopin, "Marble Ciborium with Greek Inscription," in *The Treasury of San Marco, Venice,* ed. D. Buckton (Milan, 1984), 96–7.

31 K. J. Conant, "The First Dome of St. Sophia, and Its Rebuilding," *Bulletin of the Byzantine Institute* 1 (1946), 71–8, ventured a detailed graphic reconstruction. More recently, scholars have become weary of graphic reconstructions. Thus, Mainstone, *Hagia Sophia,* 91–3, 96, and 209–12, figs. 115b and 237, offers but a schematic cross section. The problematic springing point of this dome in relationship to the presumed cornice, which would have been essentially identical to the present one, however, is maintained. This detail will require further attention.

32 Harrison, *A Temple,* fig. 169.

33 D. Talbot Rice, "Excavations at Bodrum Camii 1930," *Byzantion* 8 (1933), esp. 158–62, refers to it as a bath (or a baptistery) and dates it in the sixth century; Müller-Wiener, *Bildlexikon,* merely observes "der aber nicht in achsialer Beziehung zum Rundbau steht" (240).

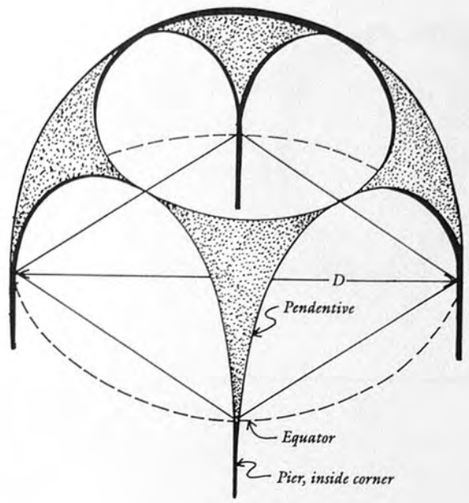


Fig. 24. Pendentive dome. (From R. Mark)

Fig. 25. Marble ciborium shrine, Treasury of San Marco, Venice. (From *The Treasury of San Marco, Venice*)

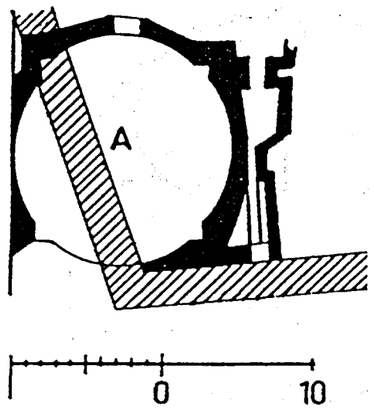


Fig. 26. "Small Myrelaion Rotunda," Istanbul; plan. (From W. Müller-Wiener)

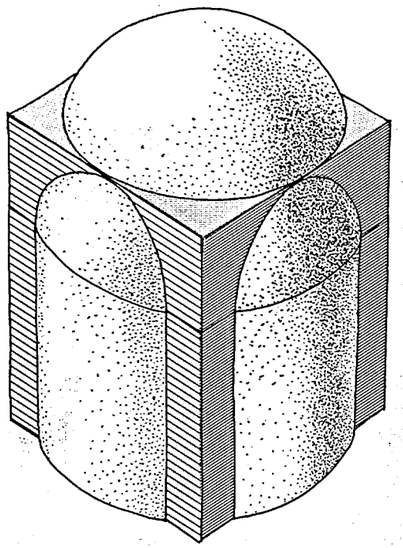


Fig. 27. "Small Myrelaion Rotunda," Istanbul; volumetric reconstruction. (Drawing: author)

of the dome of Hagia Sophia and equal in size to the diameter of the dome of Hagia Eirene, the second-largest Byzantine church to have survived in Istanbul. The plan of our rotunda features a circle with four projecting right-angle corners whose alignment approximates a square in plan. Thus, the planning scheme would seem to have involved a juxtaposition of a circle and a square or, in three-dimensional terms, of a cylinder and a square prism (Figure 27).[34]

34 A building of a remarkably similar plan, but of slightly smaller dimensions (9.7-m interior diameter) has recently come to light in Hadrian's Villa at Tivoli; see F. Rakob, "Ambivalente Absiden: Zur Zeichensprache der Römischen Architektur," *Mitteilungen des Deutschen aarchaeologischen Instituts: Roemische Abteilung* 94 (1987), esp. 21, plate 9.1, and foldout plan. The fact that this building was completely open on one side, and its relatively thin walls, preclude, in my opinion, the possibility of it having been domed.

If my hypothetical reconstruction of this building is correct, its cylinder would have been crowned by a hemispherical dome, the four segments of which would have doubled as vaults over the four shallow lateral exedras, the depth of which was determined by the intersection of the principal circle and the square. The dome under these circumstances would have been a pendentive dome, while the four pendentives would have had broad bases supported by L-shaped piers. The four exedras would have provided natural buttressing for the main dome, possible only in a building of a strictly centralized plan. As such, this scheme would have been of vital importance for the general development of the pendentive dome, and in particular would have been a crucial Byzantine forerunner of the first dome of Hagia Sophia.

Principle 3: Domes in Multiniched, Domed Buildings

Late Antique multiniched domical buildings using various basic polygonal plans – decagons, octagons, and hexagons – are known from the fourth to the early sixth century.[35] The decagon is illustrated by the well-known hall, or nymphaeum, in the Licinian Gardens in Rome (ca. 300); the octagon, by the Roman building near Palestrina (possibly also ca. 300); and the hexagon, by the funerary structure in the cemetery of Praetextatus in Rome (second half of the fourth or early fifth century).[36] These schemes, taken collectively, illustrate the scope of experimentation with domed buildings during this period. This experimentation was spurred by a variety of needs, ranging from functional to symbolic. The problems incurred likewise ranged widely, from architectural integration of such spaces into larger contexts to the structural integrity of the domes themselves. On a general plane, and for a number of independent reasons, it would appear that domes supported on fewer supports gained favor with the passage of time. This trend, in fact, may have played a decisive role in the ultimate appearance of the pendentive dome based on a square plan and supported on merely four points.

The obvious advantages of such a unit in the realm of architectural compatibility within larger contexts derive from its modular properties and its potential for spatial and structural integration.[37] Another aspect pertaining to the geometric articulation of pendentive domes related to different plan schemes may have been equally important, and deserves further consideration here. It will be noted that the size of the exposed shell varies from one plan scheme to another. In dealing with pendentive domes based on a fixed diameter of the hemispherical shell, we note that the greater the number of sides in the polygonal base, the greater the segment of the shell, and vice versa. As illustrated in Figure 28, the exposed shell of an octagonal scheme is the largest, whereas that of the square scheme is the smallest. The latter scheme was

35 H. Windfeld-Larsen, "L'hexaconque funéraire de l'area sub divo de cimetière de Pretextat à Rome," *Acta ad archaeologiam et artium historiam pertinentia* 4 (1969), 61–93, discusses a wide range of functional and formal issues within a broad chronological framework, from Late Antiquity into the Middle Ages.

36 Ibid., plate 13 (Licinian Gardens) and plate 6 (Cemetery of Praetextatus). M. Salmi, "Influssi degli edifici antichi di culto sulle chiese dell' alto medioevo in Italia," *Atti del IV Congresso internazionale di archeologia christiana* (Rome, 1948), 2: 258 and fig. 21.

37 Krautheimer, *Early Christian and Byzantine Architecture*, 238–9.

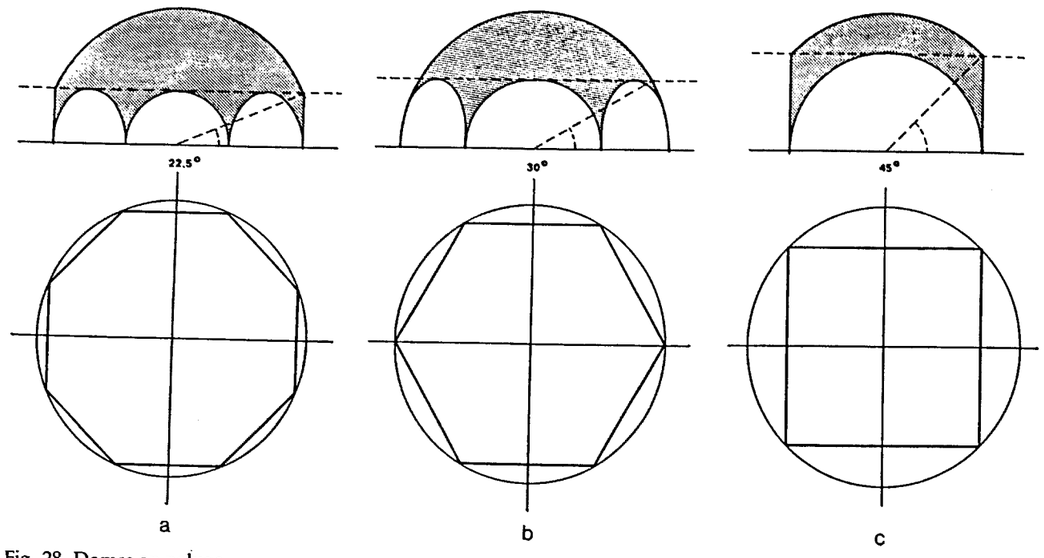


Fig. 28. Domes on polygonal plans. (Drawing: Christoph Panfil)

employed, as we have already seen, in the first dome of the Hagia Sophia and most likely in the dome of the "Small Myrelaion Rotunda." The articulation of these domes would have given a very distinctive dormal character to these buildings. The rationale for this choice, as we shall see, was apparently governed not by aesthetic, but by structural considerations.

Principle 4: "Crack-Free" Domical Shell

Recent studies of the structural behavior of ancient masonry domes by Rowland Mainstone and Robert Mark have shown that hemispherical domes were prone to radial cracking.[38] Their theoretical analyses have led to the conclusion that the cracking of hemispherical masonry domes was an unavoidable by-product of the geometry of these domes. The structural explanation, to put it in the simplest terms, is that approximately the lower two-thirds of such domical shells are subjected to tensile forces, whereas the upper third is subjected to compressive forces. Because masonry in general behaves poorly in tension and well in compression, the lower portions of such masonry domes, in accordance with this hypothetical model, can be expected to develop radial cracking. Studying the Pantheon in Rome, Mark has found confirmation of the model in the very fabric of its dome, as well as in other surviving examples of its progeny, such as the fourth-century so-called Tempio delle Tosse in Tivoli.[39] The phenomenon is actually widespread and consistent.

Mark has made another important theoretical observation regarding the

38 R. J. Mainstone, *Developments in Structural Form* (Cambridge, Mass., 1983), 42–4; idem, *Hagia Sophia* 165 and fig. 191; Mark, *Light, Wind, and Structure*, 64–5.
39 Mark, *Light, Wind, and Structure*, 65–7 and figs. 3.12 and 3.13.

behavior of hemispherical domes – that the hypothetical parallel separating the portion of the dome in tension from that in compression lies at approximately 54 degrees from the base of the dome.[40] Keeping this in mind, we will note that the segment of the shell of a pendentive dome based on a square plan begins at 45 degrees from the horizontal. As such, the pendentive dome, at least from the point of view of the preempting potential radial cracking, would have been the most effective solution among those available to ancient builders. It should be observed that the hexagonal scheme with its 30 degrees from the horizontal, and the octagonal scheme with only 22.5 degrees, would have clearly been less desirable from this technical point of view.

The question arises: Did the ancient builders have such sophisticated knowledge of structural behavior, or at least did they have sufficient statistical information about past problems? Written sources, as might be expected, are completely silent on these matters. Our conclusions, then, must be based on the observations of the buildings themselves. Unfortunately, the key monument in this category – the first dome of Hagia Sophia – is not available for technical scrutiny. We do have, however, another important surviving building that, I believe, confirms the extent of such knowledge. The building in question is the Mausoleum of Theoderich in Ravenna (Figure 29).[41] Built as a monumental mausoleum for the Ostrogothic ruler, it was completed, in all likelihood, around 526, the year of Theoderich's death. As such, its construction would have preceded the rebuilding of Hagia Sophia by a few years.

The Mausoleum of Theoderich has long attracted the attention of architects and scholars largely because of its idiosyncratic nature, and above all because of its shallow dome carved out of a single block of stone. Measuring nearly 11 m in outer diameter and weighing around 300 tons, this dome has been hailed as an engineering tour de force.[42] Its shallow profile with its twelve "ears" has been compared to the first dome of Hagia Sophia, as well as to the tombs of Germanic chieftains.[43] Yet a particular aspect of its design has totally escaped attention. This monolithic dome, as can be observed (Figure 30), is a segment of a much larger hypothetical hemisphere whose diameter measures 8.6 m and whose base coincides with the floor plane of the upper story of the mausoleum. Furthermore, it should be noted that the baseline of the actual dome forms an angle of 54 degrees with respect to the baseline of the hypothetical hemisphere. In other words, as we have seen from Mark's theoretical observations, the geometry of this dome fits exactly the prescribed limits of safety and as such is free of radial cracking.

The Mausoleum of Theoderich, therefore, would appear to confirm a high level of design sophistication that took into account a fundamental principle related to the structural behavior of masonry domes. Clearly, this knowledge could not have depended on anything comparable to modern theoretical analyses. Instead, it must have been based on the cumulative experience in the construction of domes during the preceding two centuries. This, in turn, puts it into the mainstream of Byzantine structural engineering and brings into

40 Ibid., 65.
41 R. Heidenreich and H. Johannes, *Das Grabmal Theoderichs zu Ravenna* (Wiesbaden, 1971).
42 G. Tabarroni, "La cupola monolitica del Mausoleo di Teodorico: Problemi tecnici e interpretativi," *Felix Ravenna*, 4th ser., 5–6 (1973), 119–42. The estimated weight of the dome varies widely among the different authors (from 300 to as high as 470 tons).
43 Krautheimer, *Early Christian and Byzantine Architecture*, 273.

Fig. 29. Mausoleum of Theoderich, Ravenna; exterior. (Photo: author)

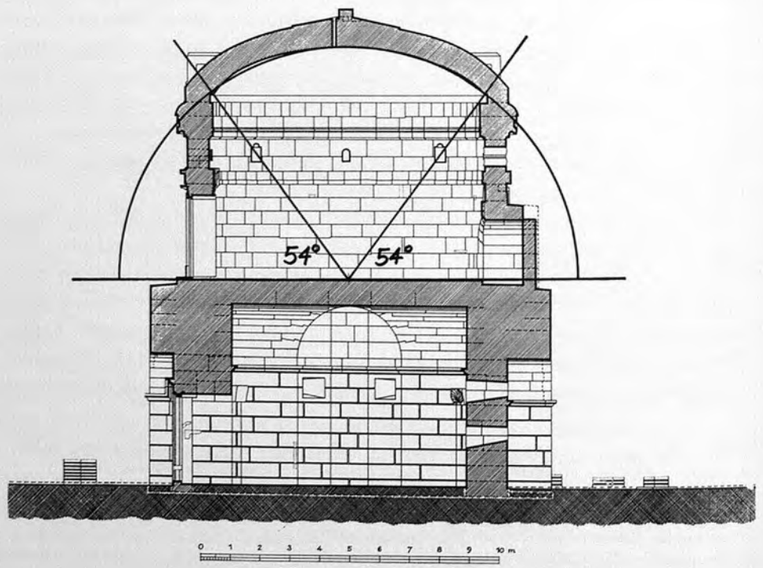


Fig. 30. Mausoleum of Theoderich, Ravenna; section. (From R. Heidenreich and H. Johannes)

question the alleged provincial origin of its builders. Without wishing to revive old controversies, I believe that the time has come for a new, engineering study of this extraordinary monument.

Principle 5: Grille Foundations and Bilateral Symmetry of Domed Units

The elongated plan of Hagia Sophia brings into focus the essential dilemma faced by its architects: how to reconcile a domed, centralized unit with a basilican, longitudinal plan. How did Anthemius and Isidorus respond to this challenge in laying the foundation walls for their great building? Unfortunately, we do not know the answer to this important question. The foundations of Hagia Sophia have never been explored. In contrast, the excavated remains of Hagios Polyeuktos reveal everything that remains invisible in the case of Hagia Sophia, and thus possibly offer some important clues. Its two massive, parallel foundation walls respond at once to the basilican format and to the need for a vaulted superstructure, presumably including a centrally located dome.

The key factor here, as I see it, is that architects around 500 were apparently still thinking conservatively when it came to laying out the foundations of these new church types. Notwithstanding their avant-garde design intentions regarding the introduction of domed units, their structural know-how in the realm of foundations was thoroughly old-fashioned. The foundation walls of Hagios Polyeuktos, as well as the superstructure of Hagia Sophia, suggest that the architects in both cases were ignorant of an important structural principle – the bilateral symmetry of domed units.

Later Byzantine church architecture illustrates the rectification of both problems. The naos of Hagia Eirene in Istanbul, as rebuilt after the earthquake of 740, shows the extension of lateral arches supporting the dome into deep barrel vaults reaching the exterior of the building. Thus, a bilaterally symmetrical cross-domed unit was created, as an afterthought.[44] Likewise, foundations of later Byzantine domed churches reveal the use of bilaterally symmetrical grille foundations. These comprise a matrix of longitudinal and transversal foundation walls, intersecting at salient points, as the thirteenth-century so-called Church E at Sardis illustrates (Figure 31).[45]

The initial stages of the development that led to this level of sophistication in the structural layout of foundations occurred, in my opinion, as early as the sixth century, in Constantinople. To illustrate my point, I shall refer to two church buildings excavated since World War II. The two are of a generally similar architectural disposition, and of a comparable scale, both measuring around 22 m in length. The first was excavated near the Beyazit Square, within a cluster of Early Byzantine churches. It was labeled Church C by its excavator, Nezih Firatli, who dated it to the first half of the sixth century

44 U. Peschlow, *Die Irenenkirche in Istanbul: Untersuchungen zur Architektur* (Tübingen, 1977), 208–13.

45 H. Buchwald, "Sardis Church E: A Preliminary Report," *Jahrbuch der Österreichischen Byzantinistik* 26 (1977), 273–5 and fig. 4.

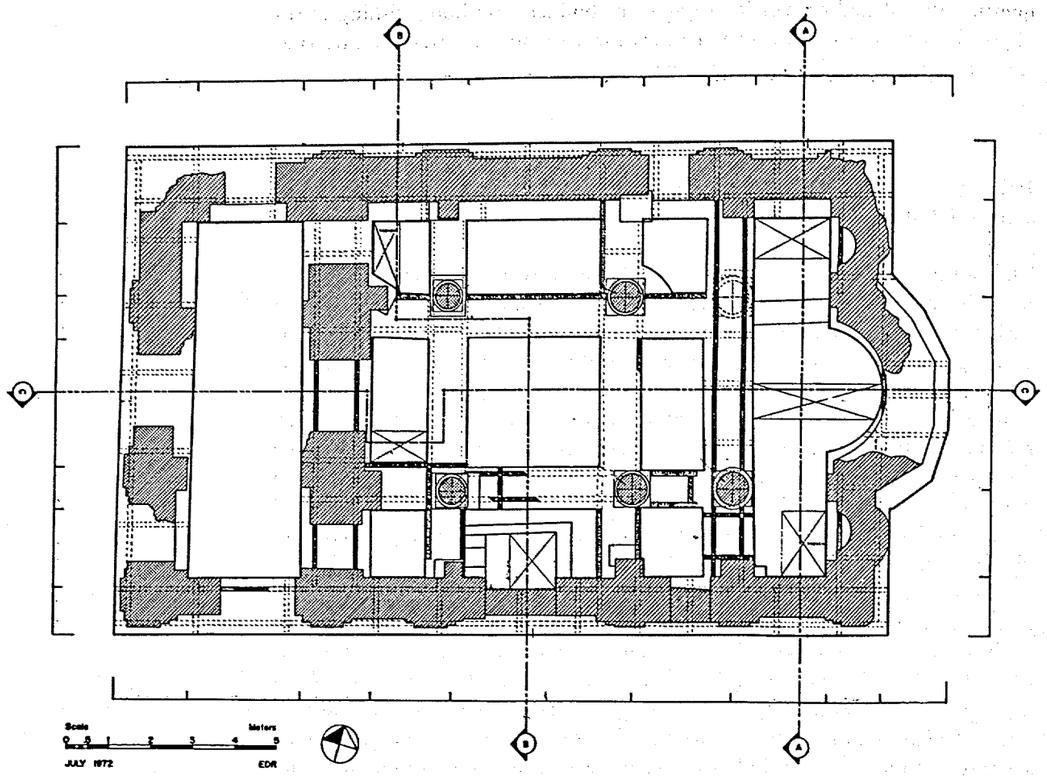


Fig. 31. Church E, Sardis; plan of foundations. (From H. Buchwald)

(Figure 32).[46] The second building has been tentatively identified as the baptistery of the church of Hagios Polyeuktos and has been dated by its excavator, Martin Harrison, to 524–27 (Figure 33).[47] The two buildings share similarities in layout, both displaying a square central bay, which may have been originally domed. Despite the apparent similarities, the two buildings also reveal major differences. This is especially evident in the disposition of their foundation walls. Church C has two parallel, east–west foundation walls flanking the central square. By contrast, the baptistery of Hagios Polyeuktos reveals a system of longitudinal and transversal foundation walls fully framing the central square. The former solution would seem to be consistent with basilican planning, notwithstanding the introduction of a square central bay. The latter fully responds to the central square bay, providing the most rational foundation solution fully adopted in later Byzantine practice.

The foregoing brief analysis of some of the design and structural aspects among the Byzantine precursors of Hagia Sophia suggests that the Great Church

46 N. Firatli, "Découverte de trois églises byzantines à Istanbul," *Cahiers Archéologiques* 5 (1951), 163–78. See also T. F. Mathews, *The Early Churches of Constantinople: Architecture and Liturgy* (University Park, Pa., 1971), 69, who dates the building, I believe erroneously, to the Middle or Late Byzantine period.

47 Harrison, *A Temple*, 64.

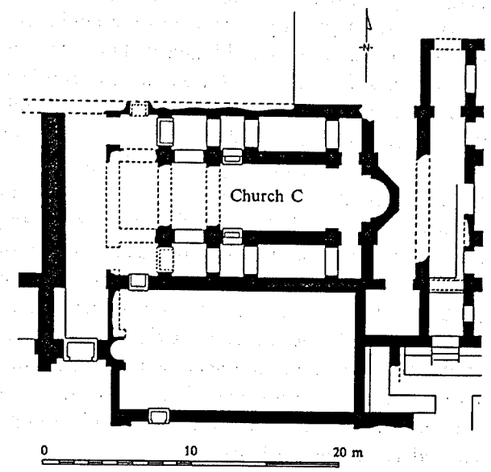


Fig. 32. Beyazit Church C, Istanbul; plan. (From T. Mathews)

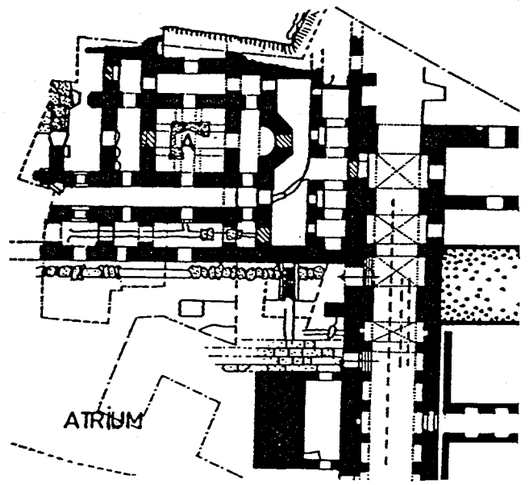


Fig. 33. Hagios Polyeuktos, Istanbul; baptistery, plan. (From W. Müller-Wiener)

was not created in isolation. Notwithstanding the dearth of information and the established notion of standardized, conservative construction that preceded the creative outburst in the age of Justinian, the fifth century, as we have seen, was characterized by considerable structural experimentation. As might be expected at any time in the preindustrial era, "structural experimentation" was a very gradual process the results of which often have to be gauged over a period of several decades or more. It would appear that through the slow but steady mastery of certain fundamental structural principles Early Byzantine architects evolved and perfected their new design concepts. The creative vitality of these architects is best demonstrated through their successful synthesis of symbolic intention and structural pragmatism. The church of

Hagia Sophia, without a doubt, constitutes a high point of this synthesis. The greatness of Hagia Sophia rests not merely in its complexity and its "absolute originality," as some would have it, but in the ingenuity and skill with which its architects integrated and molded a multitude of previously tested concepts into a new whole. At the same time, Hagia Sophia serves as a reminder that the creative process that shaped it *was* a continuum. Many of the design and structural solutions employed in building it were not fully resolved, indicating insufficient previous experience for certain principles to have been satisfactorily articulated. It was left for the following generations of Byzantine builders to recognize the need for grille foundations or to resolve the problem of bilateral buttressing of the dome base, to mention only two fundamental problems whose solutions were not reached until *after* Hagia Sophia was built. It was through the mastery of *those* issues that further design innovations evolved. The creation of the cross-in-square scheme, which many view as the Byzantine architectural paradigm, was the ultimate product of this creative process. In it, structure, symbolism, and iconography reached what must be viewed as a perfect balance.

OBSERVATIONS OF THE FABRIC OF THE BYZANTINE HAGIA SOPHIA AND RELATED BUILDINGS

BYZANTINE WRITERS ON THE FABRIC OF HAGIA SOPHIA

CYRIL MANGO

By contrast to that of the Ottoman period, the Byzantine evidence for Hagia Sophia does not contain any documentary material, such as technical reports, contracts, or bills for work carried out. We may imagine that such documents once existed in the imperial and patriarchal archives, but none has survived. Except for one inscription, to which I shall return presently, all of our evidence is literary in the sense that it is embedded in compositions meant for reading or recitation, that is, histories, chronicles, works of rhetoric, lives of saints, and so on. Thus, the original construction by Justinian is recorded by Procopius, the collapse of 558 by Malalas, the subsequent rebuilding by Agathias, and the church as rebuilt by Paul the Silentiary and Evagrius. The repairs of Basil I are briefly mentioned in the *Vita Basilii*, the collapse of 989 by Leo the Deacon and Skylitzes, and the erection of exterior buttresses in the early fourteenth century by Nicephorus Gregoras, who, along with Cantacuzenus, speaks of the collapse of the dome in 1346 and the following repair. Nearly all of this material has been available in print since the seventeenth century and has been duly excerpted by scholars starting with Du Cange. The latest addition to the dossier, if I am not mistaken, is a twelfth-century rhetorical description of the building by one Michael, nephew of the archbishop of Thessalonica, published in 1960 by John Parker and myself.[1] It would be both tedious and unprofitable if I were to comment on all the Greek sources bearing on the history of the fabric from 532 down to the Turkish conquest. To be sure, some of them are now available in more accurate editions than those used in the past, and we are more aware of the mutual relationship among sets of derivative sources (in particular the chronicles), but that hardly calls for a regurgitation of the entire dossier. Where an advance can be made is in what may be called the "topography" of Hagia Sophia, that is, both the nomenclature and the use of its constituent spaces and surrounding adjuncts. A first attempt in that direction was made by Jean Ebersolt, largely on the basis of the Book of Ceremonies of Constantine Por-

1 "A Twelfth-Century Description of St. Sophia," *Dumbarton Oaks Papers* 14 (1960), 233–45.

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phyrogenitus.[2] There is a good deal to add to this topic, in particular from a neglected Typikon (i.e., book of liturgical ritual) that is preserved at Dresden, unfortunately in a mutilated condition as a result of bombing during World War II. A discussion of this important source will have to await another occasion.

Before we proceed, I should say a word about the one inscription that tells us something about the history of the structure. The inscription was placed in the main eastern arch and recorded its consolidation by the emperor Romanus III (1028–34), which is not mentioned in any written source. The inscription, which was in mosaic and the complete text of which was copied into several manuscripts, was still visible in part in the early years of the nineteenth century. Now that the mosaics of the eastern arch have again come to light, it would be interesting to find out if the inscription still exists or has left any traces in the place where, some time ago, I argued it probably was;[3] and if it is indeed discovered, it would also show what portion of the earlier, Justinianic arch was incorporated into the rebuilding after the collapse of 1346.

As I have said, the written Byzantine evidence for the structural history of Hagia Sophia is of a literary nature, which means that it has been passed through a kind of sieve. Setting aside the role of political or personal bias, authors are subject to certain conventions of genre, style, and language. Byzantine authors of the more elegant kind avoided technical descriptions and the technical vocabulary necessary to express them. They adopted instead the language of ancient rhetoric, laboriously paraphrasing familiar terms into archaic circumlocutions that were considered more appropriate. That has been remarked many times and I do not wish to labor the point here. What may be worth stressing, however, because it is less obvious, is that for Byzantine authors the boundary between fact and myth was not the same as it is for us. The two texts I have chosen to discuss will, I hope, lend some substance to this observation.

The first is the text we all have to start from, namely, Procopius *De aedificiis*, I.1.20–65. It forms the opening section of a lengthy and possibly unfinished work devoted to the buildings put up by the emperors Justin I and Justinian in many, if not all, parts of their empire. The description of Hagia Sophia was composed with particular care and was probably intended for oral recitation on some suitable occasion. Before we can evaluate it, we have to answer two questions: When was it written and why?

As to date, there are two conflicting opinions, the first ca. 554, the second ca. 560. The earlier one[4] is based, first, on the absence of any reference to the collapse of the dome (7 May 558) and, second, on the description of the Samaritans in Palestine as peaceful citizens, whereas they staged a bloody revolt in the summer of 555. The later date, argued, among others, by G. Downey[5] and, more recently, by M. Whitby,[6] hinges on the bridge of the river Sangarius (Sakarya), which Procopius (V.3.10) describes as being still unfinished,

2 *Sainte-Sophie de Constantinople: Etude de topographie d'après les cérémonies* (Paris, 1910).
3 *Materials for the Study of the Mosaics of St. Sophia at Istanbul* (Washington, D.C., 1962), 69–70.
4 E. Stein, *Histoire du Bas-Empire* (Paris, 1949), 2: 837.
5 "The Composition of Procopius' *De Aedificiis*," *Transactions of the American Philological Association* 78 (1947), 182–3; see also J. B. Bury, *History of the Later Roman Empire* (London, 1923), 2: 428.
6 "Justinian's Bridge over the Sangarius and the Date of Procopius' *De Aedificiis*," *Journal of Hellenic Studies* 105 (1985), 141–8.

whereas the chronicler Theophanes (*anno mundi* 6052) places the start of its construction in 560. Personally, I am convinced that the earlier date is right, at any rate for the part of the text that concerns us here, for reasons I shall explain shortly; but that still means that the description was written about twenty years after the erection of Hagia Sophia. Furthermore, Procopius could not have witnessed the process of construction, except, perhaps, in its initial stage in 532, for between 533 and 540 he was abroad, first in Africa, then in Italy.[7] We do not know, of course, the exact timetable of construction, but it is fairly safe to assume that the colorful anecdotes told by Procopius reached him secondhand. Our author returned to Constantinople in ca. 540, when he must have seen the completed cathedral.

It is evident to me, if not to everyone else, that the *De aedificiis* is a reflection of official propaganda, that is, of the views that Justinian's government wished to impose on the public. Why Procopius should have consented to write such a work is not at all clear. Procopius regarded Justinian with profound hatred, which he vented in his *Secret History*, written in 550, but certainly withheld from publication. In his *History of the Wars*, completed in 553, he was also critical of the emperor, but in a much more guarded manner – between the lines, as it were. If an appreciable lapse of time had separated the two historical works from the *De aedificiis*, it might have been possible to argue that Procopius experienced meanwhile a change of heart; but the interval was so short – barely a year or two between the last book of the *Wars* and the *De aedificiis* – that a shift of 180 degrees from unbounded detestation to servile admiration can hardly be accepted. And if, as I have no doubt, the true views of Procopius are contained in the *Secret History*, it follows that the *De aedificiis* was written under some pressure or constraint. That it was commissioned and that Procopius was furnished by government departments with lists of completed buildings, many of which he had never seen himself, can furthermore be deduced from a number of passages.

We may conclude that what Procopius says about the process of the construction of Hagia Sophia – and it is the best account at our disposal – is neither candid nor due to autopsy. Let us examine it bearing these considerations in mind. It can be divided into two components, one descriptive, the other anecdotal. Seeing that the text of Procopius is our only written evidence for the appearance of the building before the collapse of 558, we are naturally led to scrutinize it very carefully with regard to any features of the original design that were subsequently altered. We are told without any ambiguity that the first dome had windows and rested on pendentives. The brief statement about the tympana, however, is open to doubt: They were made up of some kind of masonry and contained columns that were either very long or rather small, depending on whether we read *makrous* with the Vatican manuscript or *mikrous* with the others. Personally, I would opt for the long columns on the assumption that the tympana were pierced by large glazed windows like the western arch, but that is not something that can be securely deduced from the text.

The rest of the architectural description does not tell us anything we do not already know, although it is interesting to note the features that Procopius chooses to emphasize and those he ignores. First and foremost comes the

7 Stein, *Histoire*, 711.

luminousness of the interior, especially at sunrise. Even today, when the interior has been considerably darkened by the walling up of openings, the loss of gold mosaic, and the accumulation of dirt on the marble, the play of light in the early morning is unforgettable. The multicolored marble is also singled out, but that is a regular feature of all Byzantine descriptions of buildings. Of the precious adornments only the silver revetment of the sanctuary, weighing 40,000 pounds, is specifically mentioned. The figure is not unreasonable, but naturally could not have been arrived at by simply looking at the revetment. The wonderful ambo, the chancel, the altar table with its ciborium are all left out.

The actual account of the construction turns out to be rather meager. The first step, we are told, was to gather craftsmen from all over the earth and to engage, providentially, the services of two outstanding architects, Anthemius and Isidore. The architects' task was to prepare designs in advance, to supervise the work force, and, in general, to assist (*hypourgein*) the emperor. The notion that the architects were acting in a merely supporting capacity need not surprise us, being as it was part of the imperial fiction of those days. Nothing else is said about the course of construction except the use of lead in the piers and two anecdotes featuring Justinian's inspired intervention. As to the lead, Procopius is certainly in error when he states that it was poured into the joints and then allowed to harden: It must have been used, if at all, in sheet form, as Paul the Silentiary more plausibly states (*Description of St. Sophia,* 476–80). I do not suppose that Procopius ever saw the lead being used, and he certainly did not witness the two instances of Justinian's intervention, both of which concern the main arches. The first intervention involved the eastern arch, which, as I understand the text, was being built on centering. Before the crown had been reached, the supports, overburdened by the weight of the masonry they were carrying, began to break away. Here the translation by Dewing and Downey appears to me faulty: It was not the piers that began to crack, but the centering.[8] Furthermore, it was not Anthemius and Isidore who rushed to the emperor in despair, but members of their staff (*hoi amphi te Anthemion kai Isidoron*) – admittedly a slight difference. The emperor, inspired by God, ordered them to complete the arch, whereupon it stood of its own accord, no longer needing the centering underneath.

This incident carries an implication that, I believe, has not been noticed. It was precisely the eastern arch that collapsed in 558. Would Procopius, knowing that, have written that Justinian by divine inspiration had made it stand secure? Surely not. Hence, the text was written before 558.

The second imperial intervention concerning the north and south arches is to me less clear. It appears that the tympana walls were built while the arches above them were still damp (i.e., had not set properly) and that resulted in a downward compression, which caused certain unspecified columns to throw off small flakes. Justinian directed a portion of the tympanum membrane that came into contact with the arches to be removed and replaced after a lapse of time, when the masonry had dried out.

Procopius does not claim to have witnessed Justinian's felicitous interven-

8 My own rendering in *The Art of the Byzantine Empire* (Englewood Cliffs, N.J., 1972), 77, should also be corrected.

tions, although he assures us that others had. I do not know whether he expects us to believe them any more than he intends us to take literally his statement that the burning of the Theodosian church by an impious rabble had been intentionally allowed by the godhead so as to enable Justinian to put up his incomparably more wonderful cathedral. We tend to assume that these are no more than rhetorical conceits, and this may well be the correct interpretation; but it is equally possible to read the text on a more literal level and find here the first stages of the encroachment of myth upon reality – a myth that still has a certain hold on us. When we say that Justinian "built" Hagia Sophia, we tend to believe that he did rather more than instruct the appropriate financial departments to make funds available for an exceptionally imposing monument; and this belief is founded on the account of Procopius, even if we tacitly reject the supernatural element.

Our second witness takes us to another period and another conceptual world in which reality has been almost completely supplanted by myth. It is the *Diegesis* (Narration) concerning the building of Hagia Sophia.[9] If I have chosen to discuss it, that is partly because, of all the texts bearing on the cathedral, it has proved the most popular and the most influential. It was translated into Latin, early Russian, Turkish, Persian, and modern Greek. If you stop to overhear what guides today repeat to groups of tourists, you will identify much of it as deriving from the *Diegesis,* such as Justinian's exclamation, "I have vanquished thee, Solomon!" or the columns of verd antique being looted from the Temple of Ephesus or the story of the apprentice and the guardian angel. It is almost a pity to subject such charming legends to historical criticism; but even if the *Diegesis* does not give us any valid information about the sixth century, it can teach us a great deal about certain features of the building and the mentality of a later period.

It is generally accepted that the *Diegesis* dates roughly from the ninth century.[10] It is certainly later than the collapse of the early Byzantine Empire in the seventh and earlier than ca. 995, when it was incorporated into the compilation known as the *Patria*. I daresay it predates by a long time the collapse of 989. Whether it is earlier than the repairs of Basil I is not entirely clear. It appears to form part of a process of reinventing the monumental past of Constantinople, which has left us a number of textual strata that are almost impenetrable to the usual methods of criticism. We cannot help wondering in what milieu and for what reasons this reinvention was taking place.

The *Diegesis* purports to give us just what we are looking for, namely, a step-by-step account of the construction, and does so with a deceptive wealth of factual detail. It cites authorities, which turn out to be fictitious. It lists names, some of which are historical. It gives dates, some correct or possible, others widely off the mark. It quotes again and again figures of expenditure, which are obviously preposterous. What are we, as critics, to make of such a text?

The pivotal date of the *Diegesis* is the Nika Riot, placed quite correctly in Justinian's fifth year (i.e., 532). The information we are given concerning the earlier church is fanciful, but displays some historical knowledge; further-

9 Edited by Theodor Preger, *Scriptores originum Constantinopolitanarum,* (Leipzig, 1902), 1: 74–108.
10 G. Dagron, *Constantinople imaginaire* (Paris, 1984), 265–9.

more, the chronological indications add up.[11] That makes us suspect that the author has done a modicum of research. We expect to be told that the earlier church burned in the Nika Riot; instead we are informed that Justinian decided to pull it down because God had inspired him to build a temple such as had not been built since the time of Adam.

Whereas in Procopius the first step is the mobilization of a skilled work force, in the *Diegesis* it is the collection of secondhand marble elements from all the provinces of the empire, namely, columns, slabs, balustrades, grilles, and so on. Provincial governors are instructed to remove them from pagan temples, disused baths, and old houses – a statement that evokes the realities of the Middle Ages, when marble quarries had gone out of production and only recycled pieces were available. Among the marbles thus collected are singled out the eight porphyry columns, allegedly donated by the widow Marcia, and the eight big columns of verd antique, which came ready-made from Ephesus. We may note here an interesting detail: The eight porphyry columns are said to have come from Rome and to have stood in the Temple of the Sun built by the emperor Aurelian, the one who surrendered to the Persians. The emperor captured by the Persians was actually Valerian (in A.D. 260) – a small slip – but it is quite true that Aurelian did build a Temple of the Sun in Rome. Where would an ignorant Byzantine author of the ninth century have picked up this piece of information?

The collection of marble requires seven and a half years, which ought to take us to the summer of 539. Only then does Justinian demolish the Constantinian church – our author regards the Theodosian stage as representing merely a repair. Justinian puts aside the materials, of which he has no need because he has assembled more than enough for his purpose. We may remember that the enormous marble blocks of the atrium of the Theodosian church were, in fact, abandoned on the site.

The next step is the expropriation of the site, which was allegedly occupied by a number of private dwellings. I do not know whether the author has here forgotten the Constantinian church or believed it to have stood elsewhere, for in describing exactly the position of the private houses he leaves hardly any space for it. I single out two details. First, the widow Anna donates her house, which occupied the entire area of the skevophylakion, and requests that she be buried nearby. That indicates that her tomb, or her supposed tomb, was an actual feature. Indeed, there is an underground burial chamber on the north side of the church. Second, the recalcitrant eunuch Antiochus, who is unwilling to sell his dwelling, is duped by one Strategius, who is described as magister, imperial treasurer, and the emperor's adopted brother. The last item of his description is unsupported by any evidence and is inherently implausible, but we do know a Flavius Strategius, a member of the Egyptian Apion family, who was acting magister officiorum in ca. 532 and treasurer *(comes sacrarum largitionum)* from ca. 535 to ca. 538. [12] How did our author obtain that information, which is not found in any chronicle of wide circulation?

11 They are, starting from the alleged building of Constantine's church, 74+2+132=208 years. Subtracting 208 from 532 we obtain 324, which is the correct date for the foundation of Constantinople.

12 J. R. Martinale, *Prosopography of the Later Roman Empire* (Cambridge, 1980), 2: 1034–6.

The site is now surveyed and found to be on bedrock from the sanctuary to the "lower arch," which I take to be the western arch, but from there to the outer narthex the ground is loose and overgrown, and requires deep foundations. The breaking of the ground is blessed by the patriarch, incorrectly identified as Eutychius (the incumbent in 539 was Menas). So as to be able to witness the progress of the work in person, Justinian first builds the Chapel of St. John the Baptist "called the Baptistery" and a special passage from the palace, which, in fact, existed in the Middle Ages.

The work force consists of a hundred master masons each of whom has a hundred men under him, hence ten thousand in all. The chief architect is, surprisingly, named as Ignatius, but it is not he who is responsible for the plan of the church. The plan has been revealed to the emperor by an angel of the Lord. The foundations are made of huge blocks (50 cubits square by 20 high) of brick and lime mixed with the juice of barley and a decoction of the bark of elm trees. The workers are paid one silver piece per day, with the result that when the walls have barely risen 2 cubits above ground 45,200 pounds of gold have been expended. The main piers are now raised and the columns set up; the galleries are vaulted. When the structure reaches something called the second gallery and work is about to commence on the dome, the emperor runs out of money. At the prompting of an angel a delegation consisting of the aforementioned Strategius, the quaestor Basilides, and Theodore the Pumpkin, prefect of the city, are sent to the evidently abandoned suburb of Hebdomon, where they find a treasure of 8,000 pounds of gold, a paltry sum by comparison with the one quoted earlier. Note that Basilides, one of Justinian's most trusted ministers, did serve as quaestor (532–4), while Theodore the Pumpkin is a slight mistake for Theodotus the Pumpkin, prefect between 522 and 524.

Next the apse is about to be completed, and uncertainty arises about the number of windows that should light it. The emperor first opts for a single window, then for two in order to make the structure lighter, but an angel prescribes three windows to symbolize the Holy Trinity and his instructions are carried out. Special light bricks are now ordered from the island of Rhodes weighing one-twelfth the weight of normal bricks, and they are used to build the four main arches and the dome. They are laid twelve courses at a time, and then a hole is made for the insertion of holy relics. The structure is thus completed: It has taken eight years and ten months plus the seven and a half years for the collection of marble elements, which would bring us to 548, coincidentally the date of the death of the Empress Theodora, who is not mentioned at all in the text.

The author devotes a good deal of space to the adornment and furniture of the church, dwelling lovingly on the profusion of gold, silver, and precious stones. Occasionally he lets slip particulars that may well be authentic – for example, the gilding not only of the capitals, but also of cornices and the joints of the marble revetment; the existence of four altar tables; the synthronon consisting of seven steps for the clergy to sit on and having two entrances to the vaulted passage underneath, flanked by two columns each. Of the nine doors of the inner narthex leading into the nave, the three central ones are described as being sheathed in silver, the two sets of three on either side as being reveted with ivory plaques. We need not pause here over the

ambo, the relics, the plate, and lamps on which the author dwells, nor can we discuss his rather obscure reference to the fountain of the atrium and what appears to have been a pool of water at the east end of the south aisle.

When everything was ready, a total of 320,000 pounds of gold having been expended, Justinian finally celebrated the dedication on 22 December and gave thanks to God for having deemed him worthy to surpass Solomon. We are perhaps meant to understand that he had overreached himself and that the collapse of the dome was caused by his ambition and haste. If so, however, he was not made to experience the chastisement he deserved, for the collapse is dated in our text to the second year of Justin II, that is, strictly speaking, between 15 November 566 and 14 November 567, and we are further told that the original dome had lasted only seventeen years, which is one year too few with respect to the author's chronological framework. The collapse is not connected to an earthquake and, while it crushes the priceless ambo, *solea,* and pavement, it leaves all four main arches intact. The emperor Justin II calls in the architect, namely Ignatius, who is still alive, and interrogates him concerning the cause of the disaster. Technician that he is, Ignatius identifies three factors: (1) The dome was too tall; (2) its wooden centering had been removed too soon because Justinian was in a rush to decorate it with mosaic; (3) the workmen carelessly threw the timbers down to the floor, thus shattering the foundations. On the advice of experts, a new consignment of lightweight bricks is ordered from Rhodes and the dome is rebuilt 5 fathoms, that is, 30 ft, lower than the first one, and the centering is left in position for a whole year until the masonry has set properly. The ambo, *solea,* and pavement are made of cheaper materials. Finally, when the scaffolding is being removed, the church is filled with water to a depth of 5 cubits so that the falling timbers do not shake the foundations. Some people claim, concludes the author, that Justin built St. Sophia, but they are mistaken in so doing.

A reading of the *Diegesis* leaves one more than a little puzzled. Did the author know no better or did he deliberately concoct the whole story in order to drive home a moral lesson? Professor Gilbert Dagron, who has recently discussed this text with his usual acumen,[13] sees in it an implicit critique of Justinian, who squandered untold riches in his ambition to surpass Solomon, but raised an imperfect monument that had to be patched up by his more sensible successor. Indeed, it is possible to read the text in that light, and a comparison with Procopius is occasionally illuminating. Take the Nika Riot, which in both texts serves as the starting point of the story. In Procopius the earlier Hagia Sophia is burned by an impious rabble, which proves by this lawless act that it had taken up arms both against the emperor and against God. Yet this happens by God's dispensation so as to enable Justinian to build a more beautiful church. In the *Diegesis,* by contrast, the older church is not burned at all, and the riot is described as the slaughter of 35,000 people in the Hippodrome, of which Justinian is presumably guilty. In Procopius the inadequacy of the architects is corrected by the emperor's inspired advice, which causes the structure to stand secure, whereas in the *Diegesis* the emperor's imprudent haste causes the dome to collapse through no fault of the architect, who correctly diagnoses the trouble seventeen years later. If the author of the *Diegesis* had indeed this intention, we must also grant that his criticism was

13 *Constantinople imaginaire,* 191–314.

expressed with the utmost discretion and left between the lines, for the emperor is repeatedly praised for his justice and uprightness. Furthermore, we are left to wonder why an author writing in the ninth century should have wished to take Justinian to task. Was it perhaps as a lesson to a contemporary emperor – for example, Basil I, who also seems to have had Solomonic ambitions when he built the New Church in the Imperial Palace? Yet if prodigality is the main theme of the *Diegesis,* that would be much more applicable to Basil's predecessor, Michael III. An anecdote told about Michael comes to mind. He built a costly stable for his horses and, wishing to be praised for it, invited a certain learned man called Peter, hoping to be told that his memory would live forever for having put up such a splendid work. Peter said to him: "Justinian built the Great Church, which he adorned with gold and silver and precious marbles, yet he is no longer remembered. And you, O Emperor, have made a dung-heap and a resting place for horses and you wish to be remembered for that?"[14]

If Justinian was no longer remembered in the ninth century, that left plenty of scope for recomposing the story of Hagia Sophia in a manner that made sense to contemporaries. The author of the *Diegesis* was not an intellectual, but he was not a completely ignorant man. No doubt much of his information was oral, transmitted in the form of stories told about this or that noteworthy feature of the church, but he also knew about the treasurer Strategius, the quaestor Basilides, Theodore or Theodotus the Pumpkin, and Aurelian's Temple of the Sun, which would hardly have been household names. He must have derived these particulars from somewhere. I am not surprised that he had not heard of Anthemius and Isidore, whose names are recorded only by "high-style" Greek historians (Procopius, Agathias). Let us assume that our author consulted a chronicle or two. That of Georgius Syncellus would have given him Aurelian's temple;[15] that of Malalas, the dignitaries I have just mentioned, though not with the same titles.[16] If so, however, he would also have learned the correct date of the first dedication of Hagia Sophia in 537, celebrated by the patriarch Menas, that of the collapse in 558, and that of the second dedication in 562. He would have discovered that the second dome was 20 or 30 ft higher – not lower – than the first, not to mention other matters. Why did he choose to disregard these facts, and did he not expect that some of his readers might also consult a chronicle?

In asking such questions we reach the point of divergence between our mentality and the Byzantine mentality. As I said earlier, the boundary between fact and myth is not a fixed line. Our method of establishing what we regard as fact involves the sifting of evidence and the automatic rejection of anything that is unbelievable to us. To a Byzantine of the ninth century it would have been unbelievable that Hagia Sophia was built without supernatural intervention, that its design was that of an architect, that enormous columns of colored marble could have been ordered from quarries, that the whole

14 Georgius monachus (continuatus) in *Theophanes Continuatus,* ed. I. Bekker (Bonn, 1838), 825, and other chronicles of the same family.

15 *Ecloga chronographica,* ed. A. A. Mosshammer (Leipzig, 1984), 470.

16 *Chronographia,* ed. L. Dindorf (Bonn, 1831), 416 (Theodotus without his nickname), 476, 472 (Strategius without title), 475 (Basilides without title). It is also Malalas (476) who gives the number of those slain in the Nika Riot as 35,000. Malalas is now available in an English translation by E. Jeffreys, M. Jeffreys, and R. Scott (Melbourne, 1986).

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project could have been accomplished in five years, and than an emperor, even one as rich as Justinian, could have found enough cash for it. I am sure that the author of the *Diegesis* did not deliberately set out to write a fiction. On the contrary, he wished to tell the story as it happened or rather as it must have happened. The success his work enjoyed for so many centuries shows how well he satisfied his audience.

Our survey may not have taught us very much about the fabric of Hagia Sophia, but has, I hope, opened up other perspectives. An ancient text is not simply a source of hard nuggets of fact that we are free to extract from their matrix so as to build up our own "scientific" reconstruction. It is the product of its times and possesses its own logic, which we, as historians, must penetrate as far as we are able to do so.

Appendix: A Critical Calendar of Byzantine Sources

Because the treatment of Byzantine sources in the standard works on Hagia Sophia is not always entirely critical, it may be helpful to give a short survey of these sources in the form of a calendar.

Readers ought to be warned in two respects. The first concerns the imprecision of the architectural vocabulary used not only by consciously archaizing authors (who made a point of translating all "vulgar" words into their nearest classical equivalents), but also by authors writing, more or less, in everyday language. Such terms as *apsis, eilêma, pinsos, prohypostolê, stoa, and troul(l)os* are used rather loosely, and we should not expect each of them always to mean exactly the same thing.

The second caveat concerns Byzantine chronicles (as distinct from histories), that is, compilations that record events not in the manner of a connected narrative, but in the form of disparate entries placed in chronological sequence. Chronicles were regarded in the Middle Ages as utilitarian textbooks and underwent a process of continuous alteration: They were abbreviated, paraphrased, and added to. The same or nearly the same work may appear under different names. To take one example, the *Chronicle* of Ioannes Malalas (probably composed soon after its terminal date of A.D. 565) has spawned a whole family of descendants. The original text is lost – we possess only a résumé of it in Greek – but it was plagiarized by Theophanes (early ninth century), Georgius Cedrenus (after A.D. 1057), Ioannes Zonaras (twelfth century), and many others. There are occasionally interesting variants in this or that version, but we are not justified in regarding Malalas, Theophanes, Cedrenus, and others as separate sources for the passages they have in common. Essentially, we are dealing with a single source, the original wording of which cannot be entirely recovered.

To avoid needless confusion, it should be noted that there never existed an author named Georgius Codinus, who is often quoted in older discussions of Hagia Sophia, often from the obsolete edition of I. Bekker (Bonn, 1843). The name Codinus came to be attached to an anonymous fourteenth-century treatise on imperial offices and to some late manuscripts of the *Patria* of Constantinople, a compilation of ca. 995 devoted to the antiquities and monuments of the city, of which the *Diegesis* forms the fourth book. The *Patria* should be consulted in the edition of Theodor Preger, *Scriptores originum Constantinopolitanarum,* vols. 1 and 2 (Leipzig, 1901–7).

The following abbreviations will be used:

CSHB	*Corpus scriptorum historiae byzantinae* (Bonn, 1828–97)
CFHB	*Corpus fontium historiae byzantinae,* published by Association internationale des études byzantines (various places, 1967–)
Mango, *Materials*	C. Mango, *Materials for the Study of the Mosaics of St. Sophia at Istanbul,* Dumbarton Oaks Studies, 8 (Washington, D.C., 1962)
Mango, *Sources*	C. Mango, *The Art of the Byzantine Empire, Sources and Documents* (Englewood Cliffs, N.J. 1972)
Schreiner, *Kleinchroniken*	P. Schreiner, *Die byzantinischen Kleinchroniken,* 3 vols., CFHB XII/1–3 (Vienna, 1975–9)

532–7

The only reliable account of Justinian's first building is that given by Procopius, English translation by H. B. Dewing and G. Downey, *Procopius* (London, 1940), 7: 8–33; Mango, *Sources,* 72–8.

It may be noted that the date of the commencement of the construction (23 February 532) is given only in a late chronicle source and is therefore open to doubt: Leo grammaticus, *Chronographia,* ed. I. Bekker, CSHB (1842), 126. The date of the first inauguration (27 December 537) is certain, however.

537ff.

A series of earthquakes on 16 April, 19 October, and, especially, 14–23 December 557 was followed by the collapse of the eastern arch, eastern semidome, and part of the dome on 7 May 558. The rebuilding was completed before 24 December 562, when the second consecration of the church was celebrated. The descriptive poem by Paul the Silentiary was declaimed soon thereafter, perhaps on the feast of the Epiphany (6 January 563). A church hymn that may have been composed for the same occasion does not contain any specific information (ed. C. A. Trypanis, *Fourteen Early Byzantine Cantica,* Wiener Byzantinische Studien [1968], 5: 139–47).

The collapse is described as follows in the abridged Malalas, ed. L. Dindorf, CSHB (1836), 489–90 (cf. English trans. by E. Jeffreys, M. Jeffreys, and R. Scott, *The Chronicle of John Malalas* [Melbourne, 1986], 297, with indication of parallel passages):

> In the same year, when the dome of the Great Church was being restored – for it had been cracked in some places by the earthquakes which had occurred through God's Providence – suddenly, while the Isaurians were at work, the eastern part of the vaulting [*prohypostolê*] fell down and crushed the ciborium together with the holy table ["and the ambo" in some parallel versions]. The remaining part that had stayed in place was taken down, including the arches [*eilêmata*]. The dome was rebuilt 20 [Roman] ft. higher.

A fuller version appears in Theophanes, *Chronographia* (ed. C. de Boor [Leipzig, 1883], 232–3):

> In this year, on 7 May, a Tuesday, in the 5th hour, while the dome of the Great Church was being restored – for it had been cracked by the previous earthquakes – while the Isaurians were at work, the eastern part of the vaulting [*prohypostolê*] of the holy sanctuary fell down and crushed the ciborium, the holy table and the ambo.

> The engineers [*mêchanikoi*] were blamed because they had not made the suspension [*kremasis*] secure from underneath so as to avoid expense, but had bored the piers that support the dome, for which reason they had not held. Taking this into consideration, the most pious emperor erected new piers so as to uphold the dome and thus the latter was built, higher by more than 20 ft. compared to the first structure.

The following is another description in Malalas (ed. Dindorf, 495; cf. trans. by E. Jeffreys et al., 303) with reference to the second consecration:

> In the same indiction [the 11th] was celebrated the second dedication of the most-holy Great Church. Compared to its original form, the dome was raised by 30 ft., and the two arches, namely the northern and the southern ones were added.

Cedrenus (ed. I. Bekker, CSHB [1838], 1: 676–77) adds (it is not clear on what authority):

> He [Justinian] also made outside the church the four spiral ramps opposite the interior piers. These he planted in the ground and raised as far as the dome so as to buttress the arches. At the same time he made the altar table, an incomparable work. . . .

Compare parallel passages in excerpta of ecclesiastical history from cod. Paris. gr. 1555A, ed. J. A. Cramer, *Anecdota graeca e codd. manuscriptis Bibl. Reg. Parisiensis* (Oxford, 1839), 2: 114 (where Justinian is made to take down the remaining part of the dome); the so-called Great Chronographer, ed. Schreiner, *Kleinchroniken,* 1: 43, no. 12; ed. L. M. Whitby (less correctly), "The Great Chronographer and Theophanes," *Byzantine and Modern Greek Studies* 8 (1982 – 3), 19, no. 11. Zonaras, *Epitoma historiarum,* ed. T. Büttner-Wobst, CSHB (1897), 3: 170–1, is dependent on the same tradition. He has the great eastern "sphere" (semidome?) fall down in 558 and states that the new dome was 25 ft taller than the original one.

The contemporary historian Agathias, in *The Histories,* V.9.1–3, ed. R. Keydell, CFHB II (Berlin, 1967), 174–5, erroneously conflates the earthquake with the collapse. This mistake apart, he gives a very valuable account of the reconstruction:

> When, as a result of the earthquake, the church had lost the central part of its roof – the part that towers over all the others – the emperor repaired it in a more secure fashion and raised it to a greater height. Since Anthemius had long been dead, Isidore the Younger and the other engineers reviewed among themselves the former design and, by reference to what had remained, they judged the part that had fallen down, i.e. its nature and its faults. They left the east and west arches as they had been in their former places, but in the case of the north and south ones they extended inward that part of the construction which lies on a curve and gradually increased its width so as to make them [i.e., the north and south arches] agree more closely with the others and observe the harmony of equal sides. In this way they were able to reduce the unevenness of the void and to gain a little on the extent of the space, i.e. that part of it which produced a rectangular figure. Upon these [new] arches they set up once again the circle or hemisphere (or whatever else they call it) which dominates the centre of the building. As a result, the dome naturally became more even and well-rounded, conforming altogether to the [correct geometric] figure. It was narrower and steeper so that it did not strike spectators with as much amazement as before, but it was far more securely set up.

See also the English translation by J. D. Frendo, *Agathias, The Histories,* CFHB IIA (Berlin, 1975): 143–4.

Agathias is correct in indicating that the first dome had a slightly elliptical shape. That was surely due, however, to the outward tilting of the north and south arches during construction and had not been intended, as can be seen from the ground plan.

A description of the rebuilt church is given by Evagrius (late sixth century), *Ecclesiastical History* IV.31, ed. J. Bidez and L. Parmentier (London, 1898), 180–1; English trans. Mango, *Sources,* 79–80. Evagrius includes some internal measurements in feet, not all of which are easy to interpret.

A much fuller account, too long to reproduce here, is given in the hexameter poems by Paul the Silentiary, ed. P. Friedländer, *Johannes von Gaza und Paulus Silentiarius* (Leipzig, 1912), 225–65; partial English trans. Mango, *Sources,* 80–96; Italian trans. A. Veniero, *Paolo Silenziario* (Catania, 1916), 233–78. Among the statements made by Paul we may single out the following: The collapse involved the eastern arch and a portion of the dome (vv. 200–1); the rebuilt tympana had eight windows each (vv. 534–7); the baptistery was to the north of the church (vv. 563–6); there was in the south aisle a walled-off space reserved for the emperor (vv. 580–5). Paul is particularly valuable for his account of the liturgical fittings, namely, the chancel screen, ciborium, altar table, lighting fixtures, and ambo.

565–77

The southwest corner of the building, including the southwest vestibule, ramp, and rooms above them underwent some alteration in connection with the building of the Patriarchal Palace by Patriarch John III Scholasticus. This is mentioned only in a Syriac source: *The Third Part of the Ecclesiastical History of John Bishop of Ephesus,* trans. R. Payne Smith (Oxford, 1860), 145. Cf. C. Mango, *The Brazen House* (Copenhagen, 1959), 52; R. Cormack and E. J. W. Hawkins, "The Mosaics of St. Sophia at Istanbul: The Rooms above the Southwest Vestibule and Ramp," *Dumbarton Oaks Papers* 31 (1977), 200–2.

768–9

Unspecified repairs carried out by Patriarch Nicetas are mentioned by Nicephorus, Patriarch of Constantinople, *Short History,* chap. 86, ed. C. Mango, CFHB XIII(Washington, D.C., 1990), 160–1:

> At the same time Nicetas, the bishop of the City, restored certain structures of the cathedral church that had fallen into decay with [the passage of] time.

869ff.

Damage to the western arch caused by the earthquake of 9 January 869 was subsequently repaired by Emperor Basil I.

Vita Ignatii (Life of Patriarch Ignatius) by Nicetas the Paphlagonian, written ca. 907–9, *Patrologia graeca* 105 (Paris, 1862), col. 549A, records:

> Even the great church of God's Wisdom, rent in many places, would have been endangered had it not received appropriate care on the part of the emperors.

Vita Basilii (Life of Emperor Basil I), written at the behest of Constantine VII Porphyrogenitus (mid-tenth century), ed. I. Bekker, *Theophanes continuatus,* CSHB (1838), 321, states:

> The western arch of the famous holy church that has received the name of God's Wisdom – I mean the great one high up in the air – which arch had been considerably cracked and was threatening imminent collapse, he tightened up and restored thanks to the skill of his craftsmen, and so made it secure and steadfast. In it he depicted an image of the Mother of God holding in her arms her Son . . . and on either side of her he set up the chiefs of the apostles, Peter and Paul. . . . He also repaired most liberally the other fractures of this church.

The same information is repeated by Ioannes Scylitzes, *Synopsis historiarum,* ed. H. Thurn, CFHB V (Berlin, 1973), 161, chap. 41 and Zonaras, XVI.10.24–5, ed. Büttner-Wobst, 3: 434–5.

989ff.

The earthquake of 26 October 989 causes the collapse of the western arch and a portion of the dome. According to Leodiaconus, *Historia,* ed. C. B. Hase, CSHB (1828), 175–6:

> It [the earthquake] also threw down and cast to the ground the hemisphere [i.e., dome] of the upper part of the Great Church together with the western arch, which the Emperor Basil [II] rebuilt in the course of six years.

Scylitzes, ed. Thurn, 331–2, chap. 13, with the incorrect date of October, *anno mundi* 6494 (= October 985), indiction 15 (= 986–7), writes:

> As a result of a great earthquake there fell down many houses and churches and part of the dome of God's Great Church, which the Emperor liberally set up again, having expended ten *centenaria* [1000 pounds of gold] merely on the scaffolding on which the artisans stood to receive the materials that were being carried up and so rebuild what had fallen down.

These events are also recorded by the Arab historian Yahya ibn-Sa'id, who says that the rebuilding lasted four years, and the Armenian historian Asołik of Taron, who names the architect Trdat as having been responsible for the reconstruction. For a discussion of the evidence see Mango, *Materials,* 77–8. A lament on the collapse of St. Sophia, falsely attributed to Michael Psellus, the famous eleventh-century polymath, contains no specific information. It is edited by A. R. Littlewood, *M. Pselli oratoria minora* (Leipzig, 1985), no. 35, 131–4. Cf. C. Mango, "The Collapse of St. Sophia, Psellus and the *Etymologicum genuinum,*" in *Gonimos: Neoplatonic and Byzantine Studies Presented to L. G. Westerink* (Buffalo, N.Y., 1988), 167–74.

1317ff.

Exterior buttresses are erected with monies left by the Empress Irene (d. 1317), second wife of Andronicus II. Nicephorus Gregoras (d. 1360), *Byzantina historia,* VII.12, ed. L. Schopen, CSHB (1829), I: 273, states:

> For he [Andronicus] had heard from experienced builders that two of its sides, namely those facing north and east, had suffered subsidence through the ravages of time and were threatening speedy collapse if no intervention was forthcoming. For which reason the Emperor gave to the builders many thousands of gold pieces from the Queen's monies and erected from deep foundations the pyramids [i.e., buttresses] that are now to be seen, thanks to which he averted mightily the imminent danger.

1343ff.

A series of earthquakes in October–November 1343 and on 6 November 1344 are followed, on 19 May 1346, by the collapse of the eastern arch and one-third of the dome. The rebuilding was completed in 1354. Nicephorus Gregoras, XIV.2, ed. Schopen (1830), 2: 698, states:

> As a result [of the earthquakes] the damaged part of the eastern arch of the church of God's Wisdom went on gradually cracking as it sagged, letting fall many mosaic cubes and bricks until its complete collapse.

In XV.2, ed. Schopen (1830), 2: 749–51, he records:

> It was already evening under a clear sky . . . when one of the four heavenly arches (if one may say so), the one facing the rising sun, fell down, dragging down with it as much of the superimposed hemisphere [dome] as it supported. The hidden beauties of the *bema* were crushed as was also the adornment [consisting] of holy icons. . . . It was said by many persons that had it not been for the reinforcements and buttresses which had been munificently built some time previously on the eastern side by the Emperor Andronicus, the collapse would have been many times as serious and altogether irreparable.

In XXVIII.34, ed. I. Bekker (1855), 3: 198–9, Gregoras states:

> The eastern part of the great church of God's wisdom, which had been damaged ten years ago, was reconstructed immediately after the collapse, as you all know, by the Empress Anna, who was then reigning together with her son, namely [the portion] that presented the greatest difficulty, i.e. the heavenly great arch that had fallen down together with the roof of the *bema.* The small section of the hemisphere above and on either side of the arch, which was still missing, was about to be speedily completed in its turn, inasmuch as it was very small and the materials were lying in readiness, but that was prevented by this man [Cantacuzenus], who usurped her imperial power . . . and so this holy church remained neglected.

Gregoras goes on to speak of the financial aid for the repairs sent by the prince of Russia, which Cantacuzenus diverted to other purposes. See XXVIII.39, ed. Bekker (1855), 3: 201–2 (after the ordination of the Patriarch Philotheus in November 1353):

> Being ashamed of the criticism concerning the church of God's Wisdom, Cantacuzenus ordered a collection to be made among the inhabitants of Byzantium according to each man's rank . . . and thus in the space of three months the missing part of the church'es roof was completed.

Ioannes Cantacuzenus, *Historiae,* ed. J. Schopen, CSHB (1832), 3: 29–30, records:

> One year before the Emperor Cantacuzenus had taken Byzantium [3 February 1347] the church of God's Wisdom fell down in the wake of extraordinary earthquakes, not in its entirety, but [only] the big arch [*stoa*] over the *bema* and a considerable part of the roof [i.e., dome], of which over two thirds remained in place. . . . The Empress Anna, having appointed Phakeolatos to supervise the work, immediately reconstructed the big arch and *bema.* The remainder, together with the roof [i.e., dome] the Emperor Cantacuzenus later raised up and took in hand the adornment of the church as regards both marble and the setting of fine mosaic cubes. Whatever was lacking to complete the work was later carried out by the young Emperor [John V] Palaeologus, who now held alone the rule of the Romans. Both emperors were assisted in this noble endeavor by the Grand *stratopedarch* Astras, a man noteworthy in many respects and likewise skilled in building, and one of the emperor's Latin subjects called John Peralta.

The *Short Chronicles* provide the exact dates of the earthquakes and the collapse. The fullest in this respect is *Chronicle* 7: 10–11 (Schreiner, *Kleinchroniken,* 1: 65):

> In the year 6854 [1346] on 19 May, a Friday, in the night, the eastern part of the church of Hagia Sophia fell down, namely one arch and over one third of the dome, and crushed the beautiful ambo, the chancel-screen of the holy *bema* and all the holy icons.
>
> In the year 6855, on 6 October [1346], a Saturday, the conch [*myakin*] was completed together with the arch.

For a discussion of the earthquakes and the collapse, see I. Ševčenko, "Notes on Stephen, the Novgorodian Pilgrim to Constantinople in the XIV Century,"

Südostforschungen 12 (1953), 165–75; idem, "Nicolas Cabasilas' 'Anti-Zealot' Discourse," *Dumbarton Oaks Papers* 11 (1957), 167, n. 164; Mango, *Materials*, 66–8; P. Schreiner, "La chronique brève de 1352," *Orientalia christiana periodica* 31 (1965), 347–52, 360–2; idem, *Kleinchroniken*, 2: 258, 260–1, 266–7.

No specific information can be gleaned from the lament on the collapse of St. Sophia by Alexius Macrembolites, edited, together with another anonymous lament, by S. I. Kourouses, *Epeteris Hetaireias Byzantinôn Spoudôn* 17 (1969–70), 235–40, 247–50.

HAGIA SOPHIA'S NAVE CORNICES AS ELEMENTS OF ITS DESIGN AND STRUCTURE

LAWRENCE E. BUTLER

Hagia Sophia's nave cornices, ringing the nave at two levels, represent the crowning element of a much-evolved Corinthian entablature. They are also important in the structural design; as one of the very few easily accessible elements of the structure, not covered by plaster or marble revetment, they provide us with a rare opportunity to study the working fabric of the great church directly. In this essay I shall present evidence gathered from these cornices illustrating aspects of the building's design, construction, and structural history. I would like to address two questions in particular: What was the structural role of the cornice in sixth-century vaulted architecture; and what was the sequence of construction at Hagia Sophia? It is my hope that the proposed answers might illuminate a larger question: How did sixth-century architects intend their great vaulted buildings to work?

General Description of Hagia Sophia's Nave Cornices

Hagia Sophia's nave cornices comprise 216 richly carved blocks of Proconnesian marble, all of which belong to the original Justinianic campaign. They have been surveyed and illustrated in detail by Van Nice,[1] cleaned in part by

This work is based on a field study undertaken in 1983 for my Ph.D. dissertation, "The Nave Cornices of Hagia Sophia in Istanbul" (University of Pennsylvania, 1989). All credit is due to my adviser, Professor Cecil L. Striker, for bringing this extraordinary body of sculpture, with its significance and possibilities, to my attention. It is a pleasure to acknowledge the generous support of my fieldwork and subsequent research from the Fulbright commissions of the United States and Turkey, the American Research Institute in Turkey, the University of Pennsylvania, and Dumbarton Oaks. I also thank Director Erdem Yücel of the St. Sophia Museum, Professor Dr. Semavi Eyice, Professor Dr. Aptullah Kuran, Dr. Nuşin Asgari, and Dr. Anthony Greenwood for their help during my stay in Turkey. I am deeply indebted to Mr. Robert Van Nice of Dumbarton Oaks for his cooperation, advice, and encouragement and for generously allowing me to make use of his photographs and survey data.

1 R. L. Van Nice, *Saint Sophia in Istanbul: An Architectural Survey* (Washington, D.C., 1965–86), esp. plates 4, 5, 28–32A, and 36 (sections and elevations of the nave); plates 2 and 17–19 (plans at the gallery level); plates 3 and 21–3 (plans at the upper cornice level); and analytical plates 32B, 43, and

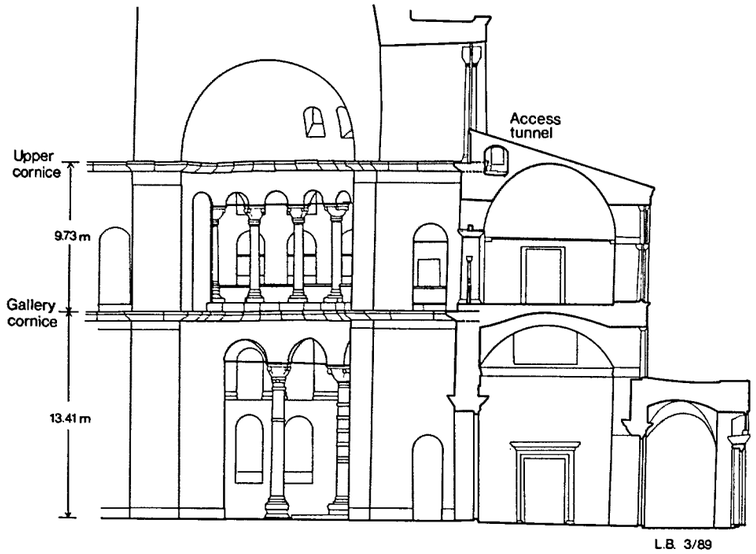

Fig. 34. Nave cornices in their structural context; section through Hagia Sophia's west nave wall, looking south. (After Van Nice, plate 32A)

Underwood, and discussed by Zaloziecky, Deichmann, Sanpaolesi, Mainstone, and myself.[2] The lower, or gallery, cornice encircles the nave and the bema, stopping short of the apse. This cornice protrudes about 71 cm from the wall below and forms a walkway roughly 75 cm wide. In profile, the carved undersurface projects out at an angle of 30 degrees from the wall and measures about 61 cm high. The gallery cornice lies just below the level of the gallery floor, and in fact supports the separate stylobate of the main gallery arcade (Figure 34). The upper cornice runs completely around the building above the gallery at the springing level of the lower vaults, some 23 m (76 ft) above the floor. The upper cornice protrudes about 52 cm at an angle of 40 degrees, and thus has a steeper profile than the gallery cornice, but is otherwise similar to it.

The gallery cornice consists of 100 blocks of Proconnesian marble, which, following Van Nice's nomenclature, we shall refer to as blocks G1 through G100, the series beginning with the first block in the southeast corner of the bema and running clockwise in plan (Figure 35). The upper cornice consists of 114 great blocks, numbered U1 through U114, and two smaller wedges,

44. Other useful illustrations of the cornices can be found in W. Salzenberg, *Altchristliche Baudenkmale von Constantinopel vom V. bis XII. Jahrhundert* (Berlin, 1854), plates 15 and 16; in A. Antoniades, *Ekphrasis tês Hagias Sophias*, 3 vols. (Athens, 1907), figs. 333, 334, and 557; and in the Dumbarton Oaks photographic archives (the Whittemore photographs taken during the mosaic restoration campaigns of the 1930s). A complete set of the author's cornice photographs is also on deposit at Dumbarton Oaks.

2 W. R. Zaloziecky, *Die Sophienkirche in Konstantinopel und ihre Stellung in der Geschichte der abendländischen Architektur*, Pontificio Istituto di Archeologia Cristiana, Studi di Antichita Cristiana (Vatican City, 1936), 12: 165–79; F. W. Deichmann, *Studien zur Architektur Konstantinopels im 5. und 6. Jahrhundert nach Christus*, Deutsche Beiträge zur Altertumswissenschaft, 4 (Baden-Baden, 1956), 3: "Das Bauornament," 76–84; P. Sanpaolesi, *La Chiesa di S. Sofia a Costantinopoli* (Rome, 1978), 181–90; L. Butler, "The Nave Cornices of Hagia Sophia: Preliminary Results of an Investigation Undertaken in 1983," *Ayasofya Müzesi Yıllığı* 10 (1985), 27–33.

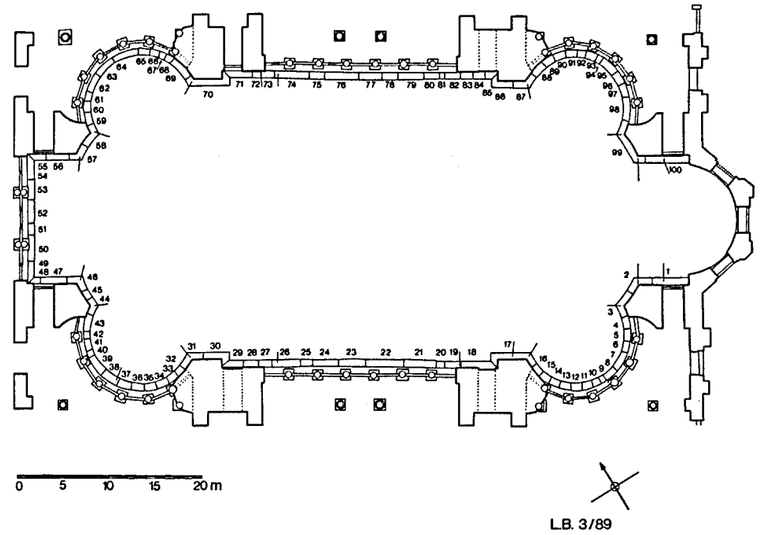

Fig. 35. Gallery cornice, Hagia Sophia; cornice blocks numbered according to Van Nice's system.

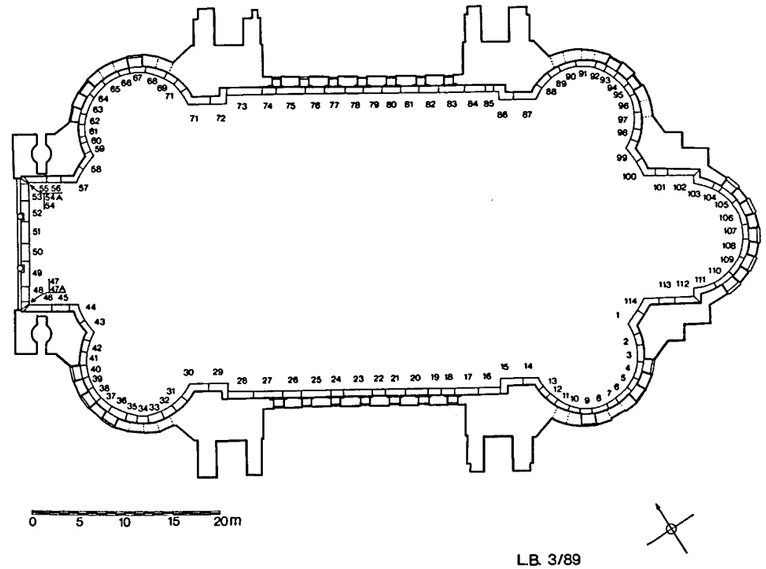

Fig. 36. Upper cornice, Hagia Sophia; cornice blocks numbered according to Van Nice's system.

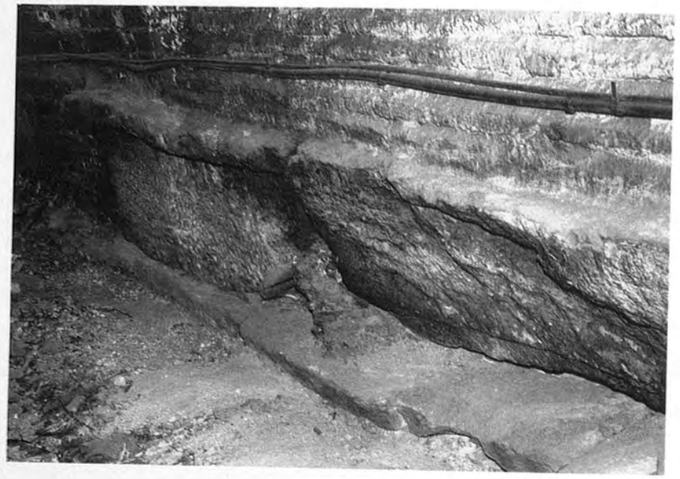

Fig. 37. Backs of upper cornice blocks U53 and U54, visible in the west access tunnel. (Photo: author)

numbered U47A and U54A by Van Nice (Figure 36). The individual blocks vary in length from less than 1 to more than 4 m in length, variously shaped in order to fit the complicated plan of the building, and most appear to extend roughly 2 m back into the masonry. At only one point in the building can one see the back sides of the cornice blocks, in the access tunnel behind the west run of the upper cornice (Figures 37 and 38). Here, in rough quarry state, they extend about 2 m into the thickness of the brick wall – in effect, the entire thickness – and rise several centimeters higher at the back than at the lip of the cornice, where the blocks have been smoothed to a uniform height. We assume that the full size, shape, and context of the gallery cornice blocks are similar, though the backs of all of them lie hidden under the bearing masonry.

The cornices appear to be in their original context, disturbed in only two places. Mainstone has demonstrated that two stretches of the upper cornice, under the north and south tympana, were rebuilt, perhaps during a late-ninth-century reconstruction (see Figure 43). The upper cornice blocks were carefully reset, and new ties were added at the ends of the rebuilt structures.[3] There is no reason to suspect that the gallery cornice has been disturbed since 537, apart from a few edges and protrusions damaged in the fall of dome masonry.[4] While the gallery columns were straightened and reset during the

3 Proposed and analyzed by Rowland Mainstone, who tested the hypothesis with limited tests of the masonry. See his "Reconstruction of the Tympana of St. Sophia at Istanbul," *Dumbarton Oaks Papers* 23–4 (1969–70), 353–68; and his *Hagia Sophia: Architecture, Structure, and Liturgy of Justinian's Great Church* (London, 1988), 97–101. The date of this rebuilding is by no means clear. This is not to be confused with the limited rebuilding that occurred during the initial construction, demonstrated by P. A. Underwood and E. J. W. Hawkins, "The Mosaics of Hagia Sophia at Istanbul: The Portrait of the Emperor Alexander," *Dumbarton Oaks Papers* 15 (1961), 187–217; for which also see Mainstone, *Hagia Sophia*, 215.

4 Close scrutiny of the gallery cornice reveals restorers' cement, disguised by stone-gray paint, creating a sharp 90-degree edge to the upper lip of many of the blocks. This restoration seems the heaviest on the south side of the gallery cornice and includes most of the blocks of the southeast and southwest exedrae, as well as blocks G18 and G21 through G26 of the south arcade run. It is thickest where major breaks in the structure occur, an apparent attempt to even up the line of the crowning fasciae of the entablature despite all the distortions of this ancient structure.

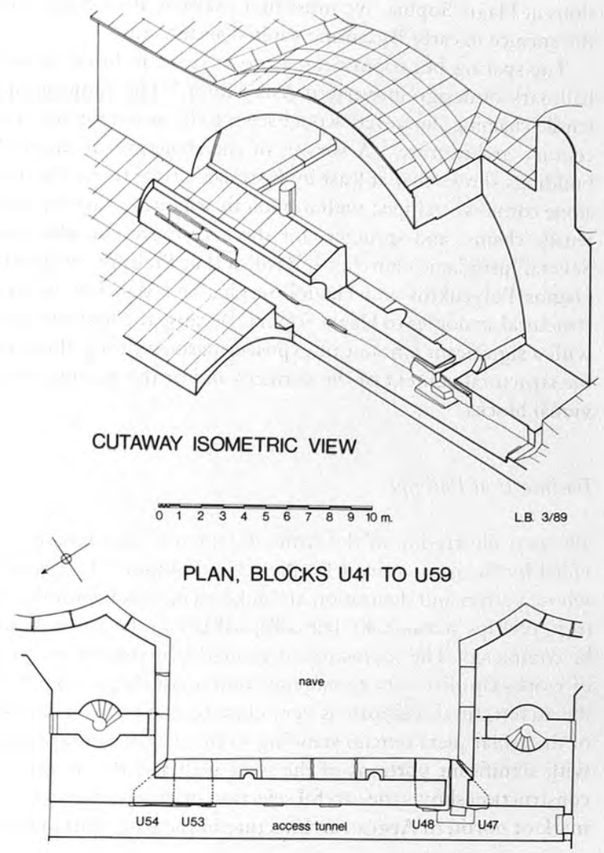

Fig. 38. Exposed cornice blocks, upper cornice, Hagia Sophia. (After Van Nice, plate 32B) Cutaway isometric view; plan, blocks U41 to U59. (After Van Nice, plate 21)

great reconstruction, the curve of the gallery cornice makes clear that it was left undisturbed. The carved decoration of the cornices also appears to be close to its original condition, except for the loss of gilding, the widespread use of stone-colored paint, and the regrettable Fossati "improvements" in black paint to the upper cornice corona soffit motifs.

Cornice Design in Sixth-Century Vaulted Structures

Domes and pendentives have always fascinated Byzantine architectural historians. Other elements of structure have not fared as well; the student seeking comparative studies of less glamorous things – cornices, for instance – must still rely on Choisy, Ward-Perkins, Deichmann, and passing references in monographs.[5] Accordingly, in order to understand the architects' inten-

5 The classic sources of information on early Byzantine structure are A. Choisy, *L'Art de Bâtir chez les Byzantins* (Paris, 1883); J. B. Ward-Perkins, "The Italian Element in Late Roman and Early Medieval Architecture," *Proceedings of the British Academy* 33 (1947), 163–94; idem, "Notes on the

tions at Hagia Sophia, we must first examine the design and construction of the cornice in early Byzantine vaulted architecture.

The sparing but sophisticated use of stone in brick vaulted structures is a hallmark of design in western Asia Minor.[6] The addition of iron cramps for tensile chaining, however, would seem to be an important innovation of sixth-century architecture.[7] A survey of the structure of major Early Byzantine buildings shows that at least by Justinian's time there was a systematic use of stone cornices, cramped with iron on their bearing surfaces, as leveling courses, tensile chains, and springers for the ever more complex vaulting systems.[8] Several Justinianic churches – Basilica B at Philippi, St. John at Ephesos, and Hagios Polyeuktos and Hagioi Sergios and Bakchos in Istanbul – provide structural analogies to Hagia Sophia. Because the first two are excavated ruins with a significant amount of exposed masonry, they allow for close study of the structural context of the cornices and of the bearing surfaces of the individual blocks.

Basilica B at Philippi

The best illustration of the structural context of a Justinianic cornice is provided by the great ruined Basilica B at Philippi.[9] The great domed basilica, whose patron and dedication are unknown, was begun in the mid-sixth century, perhaps around 540, but collapsed before the internal arrangements could be completed. The sophisticated vaulted structure seems to indicate a master of works familiar with recent and contemporary practice in the capital, while the architectural sculpture is very close to that of Hagia Sophia itself.[10] Three of the ashlar piers remain standing to the height of the second cornice, along with significant portions of the west wall and the narthex (Figure 39). The construction shows the careful selection of different materials, which is a hallmark of northern Aegean architecture in the Late Antique period.[11] The piers

Structure and Building Methods of Early Byzantine Architecture," *The Great Palace of the Byzantine Emperors, Second Report*, ed. D. Talbot Rice (Edinburgh, 1958), 52–104; Deichmann, *Studien*, passim; and more recently U. Peschlow, *Die Irenenkirche in Istanbul: Untersuchungen sur Architektur* (Tübingen, 1977), app. 1, 215–21.

6 Ward-Perkins, *Great Palace*, 52–104, passim; Deichmann, *Studien*, 1: 19–40; Peschlow, *Die Irenenkirche in Istanbul*, 215–221. The oldest standing Byzantine church in Istanbul is the ruined Stoudion basilica. Since this was not a vaulted structure, an elaborate tensile chain was not necessary. But even here, we see the cornice being treated as integral to the structure whereas the lower parts of the entablature are merely decoration applied to a flat wall.

7 According to Ward-Perkins (*Great Palace*, 62), wooden dovetail cramps were used in the foundations of the Great Palace, but there is no trace of metal – "an economy in the use of metal that is characteristic of Byzantine building methods." Choisy also thought that iron chaining was rare until Middle Byzantine times (117, 122).

8 Mainstone (*Hagia Sophia*, 77) notes the "long standing practice in comparable situations to cramp all the blocks together during construction and to do so in places where the cramps would subsequently be covered and protected by what was built above." And on pages 176 and 267, he notes that there is little evidence for the use of iron to contain thrusts in pre-Justinianic buildings except in the cramping of stone cornices or string courses. I arrived at the same conclusion independently, through my inspection of the Ephesos and Philippi material.

9 Excavated by the French school in 1914 and 1920–36, and published by P. Lemerle in *Philippes et le Macédoine Oriental* (Paris, 1945).

10 *Philippes*, 492–3, 509; restated more forcefully in Lemerle, "Autour des Basiliques de Philippes," *Revue Archéologique*, 6th ser., 34 (1949), 106.

11 It must be noted that the use of faced mortared rubble layers is rather conservative for Justinianic architecture. The massive foundations, built of mortared rubble faced with small stones, support

Fig. 39. Basilica B, Philippi; northwest pier, with cornice blocks in context. (Photo: author)

are solid ashlar, whereas the arches, vaults, and dome were brick. Many of the ashlar blocks in the piers are spolia, but were carefully fitted together and held with dovetail cramps.[12]

The cornices, made of marble ashlar blocks that extend through the thickness of the masonry, were a crucial element in this structural system, designed to act both as leveling courses and as tensile chains. Six types of structural cornice were found at the site: the modillion cornice above the six-columned nave arcades, the "great" cornice above the galleries, the dome cornice, the single apse cornice, the narthex cornice, and the impost blocks at the springing level of the nave arcade and aisle vaults.[13] All the cornice blocks were cramped together with dovetail or staple-shaped cramps, two per side

solid ashlar walls that rise to about 0.40 m. Above this, broad courses of mortared rubble faced with stone alternate with leveling courses, usually five bricks high (*Philippes*, 486). Only in the narthex is brick used predominantly, interrupted by the occasional leveling course of ashlar at the springing level of the western arches. Not all the vaults spring from a leveling course; the string course at the springing level of the vaults, for instance, appears to be merely ornamental.

12 *Philippes*, 494.

13 *Ibid.*, plate 68, shows the intricate relationship of impost and gallery cornice to the piers. These impost blocks perform an ambiguous structural function, for while they act as springer courses for the aisles and penetrate the piers deeply, they do not appear to bond with the western filler wall. The gallery cornice, by contrast, appears to have continued around the west wall, leveling a course of mortared rubble and tangentially crowning the brick arch over the main western entry, but did not act as a springing course. The others did. The gallery vaults sprang from the upper cornice, about 42 cm high, which, unusually, sat directly on the impost blocks of the gallery columns (ibid., plate 70.1 and section, plate 56).

hidden by overlying masonry in the nave cornices. The individual stones of the lower cornice measure 0.45 m high and jutted 0.55 m from the wall,[14] wide enough for a narrow catwalk, though there is no evidence of a railing. As at Hagia Sophia, a stylobate sits on top of the cornice, behind a setting line, raising the gallery floor some 0.40 m and allowing an unobstructed view of the bases of the gallery columns.[15]

Setting lines, lewis holes, and dovetail cramp holes are all apparent on the upper surfaces of the blocks lying around the site. The tooling of the blocks seems to be typical of the period: the top surface quite smooth with a setting line for the overlying masonry, the underside finely picked but smooth where the overhang is exposed. The sides exhibit anathyrosis. Lewis and cramp holes were carefully placed to be invisible when the overlying masonry was in place. In short, care was taken with the upper surface of the block, which would be visible from the gallery. The decorative carving was finished after the stones were in place, according to the evidence of several blocks from the upper cornice that had been cramped and mortared, but were incomplete.[16]

Basilica of St. John, Ephesos

The Justinianic basilica of St. John at Ephesos, a vaulted, six-domed structure contemporary with Philippi B, collapsed at an unknown time.[17] Two cornices, one above each arcade, surrounded the central spaces; only the upper cornice continued around the apse, as was usual in the sixth century. It appears that there was no separate stylobate for the gallery story, but the ongoing partial reconstruction of the walls requires caution in the drawing of conclusions regarding the structural context of the cornices.

In any case, St. John at Ephesos provides a good opportunity to study the tooling of individual cornice blocks, since a number remain on the ground free of masonry (Figure 40). The shaped blocks were smoothed with a single-point pick on the top and bottom. The exposed margins on the top and bottom were further smoothed with a claw chisel. The sides display anathyrosis, deeply hollowed with a scabbling tool in the center to leave a 1- to 1.5-cm raised strip around the edge, which was then smoothed with a claw chisel. Many still show traces of mortar. All the blocks were cramped together at the sides with metal staples, the holes for which are 4 to 6 cm square with chases up to about 8 cm to the edge of the block. Some cramp holes have lead channels. The occasional redundant arrangement of cramp holes indicates a reused piece in a new context.[18] Precisely cut lewis holes are visible toward the center of the upper surfaces.

Hörmann discusses one significant piece of masonry in detail: six cornice

14 *Ibid.*, 508–9 and plate 71. 15 *Ibid.*, 456; see section, plate 56. 16 *Ibid.*, 510.

17 Excavations begun by a Greek team led by Soteriou in 1921–2 were completed by the Austrian Archaeological Institute in 1927–31 and published by Hörmann in 1951. For the Greek excavations, see George Soteriou, "Anaskaphai tou byzantinou naou Ioannou tou Theologou en Ephesô," *Archaiologikon Deltion* 7 (1921–2), 89–226. The Austrian excavation report is by Hans Hörmann, *Forschungen in Ephesos*, vol. IV.3: *Die Johanneskirche* (Vienna, 1951).

18 See important remarks by Deichmann on the use of spolia in the cornices: "Zur Spätantiken Bauplastik von Ephesus, "*Mélanges Mansel* (Ankara, 1974), 1: 549–70, esp. 561–7.

Fig. 40. Basilica of St. John, Ephesos; upper surfaces of cornice blocks. (Photo: author)

blocks still preserved in their masonry context.[19] Judging from the profile, they come from the lower cornice of the southeast pier of the nave. The blocks, some of which were spolia, were carefully fitted to cover the entire breadth of the pier under the overlying masonry. They were cramped together with iron staples and mortared. The exposed upper surfaces were tooled smooth in situ, which lowered them as much as 4.4 cm relative to the height of the parts left rough.[20] Altogether they provided a solid, level platform for the upper masonry of the basilica piers and illustrate the cornices' intended dual structural role as leveling course and as tensile chain.

Hagios Polyeuktos, Istanbul

This is the only major sixth-century structure in the capital whose cornices have been archaeologically examined and published; however, the situation it presents is by no means clear.[21] Only in the atrium were cornice blocks found in a structural context: A fallen brick pier, some 10 m high, contained two marble cornices, a plain lower cornice and decorated upper cornice, with thirty

19 Hörmann, fig. 14: 1, and plate 26: 1, 2. 20 Ibid., 95–8.

21 Its massive foundations and splendid sculpture were discovered in the course of roadwork in 1960, and excavated and studied by R. Martin Harrison and Nezih Fıratlı from 1964 to 1967. The remains were identified as those of Hagios Polyeuktos by Cyril Mango and Ihor Ševčenko in "Remains of the Church of St. Polyeuktos at Constantinople," *Dumbarton Oaks Papers* 15 (1961), 243–7. Harrison's final report has superseded preliminary reports: R. Martin Harrison, *Excavations at Saraçhane in Istanbul, vol. I: The Excavations, Structures, Architectural Decoration, Small Finds, Coins, Bones, and Molluscs* (Princeton, N.J., 1986). Also see his *Temple for Byzantium: The Discovery and Excavation of Anicia Juliana's Palace-Church in Istanbul* (London, 1989). Erected by Anicia Juliana in the reign of Justin I, probably in 524–7, it collapsed or was razed around the year 1200, with many of its marbles soon carried off by Latin crusaders. Nothing remained intact above the foundations (Harrison, *Saraçhane*, xi–xii).

courses of brick between them.[22] The upper cornice at least was cramped, as shown by two cramp channels on one hidden side.[23]

Reconstructing the context of other blocks from the site is more difficult. The great entablature blocks with the dedicatory inscription carry no crowning member, though by analogy to Hagia Sophia they must have had one.[24] Nine stylobate blocks show column sinkings, setting marks, and anathyrosis on the sides; five are curved with radial sides. Presumably these supported the columns of the gallery.[25] It is possible that the upper cornice is represented by the thirteen blocks and thirteen fragments of type 2c. Like the upper cornice at Philippi B, they would have acted as a springing course for both nave and aisle vaults; some of the blocks have faces on opposite sides. No dome cornice was found.[26] The ruins at Saraçhane, if problematic, at least confirm general principles of sixth-century building: Stone cornices were regarded as essential structural elements, acting as springing courses, as tensile chaining, and as leveling courses.

Hagioi Sergios and Bakchos, Istanbul

The church of Hagioi Sergios and Bakchos, begun in 527 by Justinian and Theodora, represents in its design and decoration a similar desire for bold innovation.[27] The lower story is trabeated, its entablature richly decorated, while the upper story is arcuated, the arches resting on simply decorated pier capitals. The great entablature wraps around the nave at the gallery level, stopping short of the apse. There are, however, no upper cornices, neither above the gallery story nor at the base of the dome. Instead the arches and conches are supported on imposts in the piers, which perform the function of stone springers.

Since Hagioi Sergios and Bakchos is so close a forerunner of Hagia Sophia, the structural design of its entablature is of great interest. It appears that the whole height of the entablature comprises a single course of stone some 90 cm high, though thick layers of paint may obscure a joint between the frieze and cornice levels. The twenty-nine blocks are carefully designed to fit logically into the structure, reflecting the plan and elevation of the two stories. The first story of each of the eight piers is capped by a single massive entablature block that rests on two impost blocks below. Each of the seven straight and curved bays surrounding the nave comprises three more blocks, with the two columns below supporting the joints. A separate stylobate for the gallery columns sits on top of the entablature course. The visible protruding upper surface of the cornice has been evenly smoothed with a pick; only in a few places has it been smoothed further. Scars visible on the upper surface of the cornice appear to be channels for the anchoring of fifty-five or fifty-seven metal beams (Figure 41).

22 Described in Harrison, *Saraçhane,* 26–7, 411–13, and plates 69–75. A rectangular hole directly above the lower cornice was evidently for a tie beam. Block 2ci (M6931) is described on page 123, illustrated on page 125, fig. E.

23 Ibid., 411.

24 Candidates include the two groups of modillion cornice, marble types 2a and 2b (Harrison, *Saraçhane* 121, 122, and fig. C), which Harrison considers lintel hoods. Their heights, about 40 and 44 cm, respectively, would seem right. The only curved cornice pieces are his type 2h (*Saraçhane,* 126, 124, and fig. D), plain chamfered cornices that appear to be unfinished.

25 Ibid., 135, 138, and fig. I.

26 Harrison, in ibid., 408–9, admits that neither chunks of vaulting nor fragments of dome cornice came to light in the excavation and that this might cast doubt on his reconstruction of Hagios Polyeuktos as a domed structure. He claims that Hagia Sophia's second dome is the only one of the period known to have a dome cornice and that brick vaulting fragments might not be identifiable as such. The ruins of Justinianic basilicas at Philippi and Ephesos, however, would seem to contradict both these assertions.

27 For the cornice and structure of Hagioi Sergios and Bakchos, the fundamental studies are Deichmann, *Studien,* 72–6; P. Sanpaolesi, "La chiesa dei ss. Sergio e Bacco a Costantinopoli," *Rivista dell'istituto nazionale d'archeologia e storia dell'arte,* n.s. 10 (1961), 116–80; and the surveys by A. Van Millingen, *Byzantine Churches in Constantinople, Their History and Architecture* (London, 1912), 62–83, and by J. Ebersolt and A. Thiers, *Les églises de Constantinople* (Paris, 1913), 21–51.

Fig. 41. Hagioi Sergios and Bakchos, Istanbul; upper surface of cornice, showing lamp beam emplacements.

Hagia Sophia, Istanbul

Hagia Sophia's masonry is well known to be a typically Constantinopolitan mix of brick, greenstone bands in the walls, limestone ashlar piers, and marble cornices.[28] Elsewhere in the building, stone courses that penetrate the thickness of a wall are used as springers and bonding courses simultaneously.[29] The cornices follow the plan of the nave itself, with the upper cornice stopping short of the apse. The individual blocks extend about 2 m

28 Described by W. Emerson and R. Van Nice in "Hagia Sophia, Istanbul: Preliminary Report of a Recent Examination of the Structure," *American Journal of Archaeology* 47 (1943), passim; Ward-Perkins, *Great Palace,* 71–2; Mainstone, *Hagia Sophia,* 67–83, 185–6. Also note the famous passage in Procopius, *The Buildings,* I.i. 50–4, on the construction of the piers.

29 Emerson and Van Nice, "Hagia Sophia," 416, show this to be the case in the masonry of the southwest buttress. Ward-Perkins notes that Hagia Sophia's marble dome cornice "serves precisely the same structural purpose as the stone courses incorporated elsewhere in the springing of the vaults, that of providing a firm, rigid seating for the masonry of the actual cupola" (*Great Palace,* 72).

back into the masonry of the building (Figure 38), but they vary quite a bit in horizontal width, from 0.6 m to more than 5 m.

It would seem that the architects wanted to put a single giant cornice block in each of the great and subsidiary piers to make the firmest possible foundation for the upper story, as they had at Hagioi Sergios and Bakchos. Three immense blocks at the gallery level, G17, G70, and G99, each measuring about 5 m, span the width of their piers. However, this arrangement is unusual and must have proved unmanageable, since blocks of this size may weigh as much as 9 metric tons. No such arrangement was attempted on the upper cornice. Each short pier face there has one joint in the center; none is made up of a single block.[30] In most of the sixteen pier locations, therefore, the builders used two blocks in the piers, putting a single joint in the middle of each pier face.[31]

Nowhere in the straight or exedra arcades does the placement of gallery cornice blocks correspond to the placement of columns above (see Figure 46). This is certainly not due to any design change; rather, it was the separate stylobate on top of the cornice that was designed to sit squarely under the columns. If the cornices were considered part of the stylobate design, it would have been proper, in fact, to design them to be "out of phase" with the stylobate blocks. Nor does the block arrangement of either cornice reflect the arcade elevation below. Instead, the arrangement, shapes, and sizes of the cornice blocks reflect only the major divisions of pier, exedra, and straight run (Figures 35 and 36).

At the gallery level especially, the shapes and arrangement of cornice blocks are far less regular than at Hagioi Sergios and Bakchos. In the straight runs, blocks range from less than 1 m to more than 4 m in width. Though not strictly consistent, there is a pattern to their arrangement. The very small blocks occur near the point where pier masonry joins infilling arcade masonry. If my reasoning, presented later, concerning the sequence of construction is correct, then these small blocks, which show a number of inconsistencies with the blocks they abut, may have been especially planned to be fitted into this difficult space last. This pattern is not as clear on the upper cornice, but here the north and south runs are not necessarily in their original order, since Mainstone has demonstrated that the tympana, and perhaps lower parts of the gallery, was rebuilt at a later date.[32] In the exedrae, which form slightly more than a semicircle, the blocks are tapered in voussoir form. The blocks are roughly regular in size, especially on the upper cornice, where they average 1.3 m across the chord, but they are inconsistent in their curve. Some, in fact, are not curved at all.[33]

30 Even so, several enormous blocks were used in the upper cornice. The largest are U73 in the north run, adjacent to a pier, and U102 in the north bema wall. Both appear to measure less than 4 m long, but still may have weighed as much as 8 metric tons.

31 The only exception is in the southwest subsidiary pier, where at the gallery level three blocks, G44, G45, and G46, are placed where two would normally go.

32 See note 3 and Figure 43 for the limits of the rebuilding. Mainstone's exploration under the plaster showed that this reconstruction involved blocks U18 through U26 below the south tympanum and blocks U74 through U83 below the north tympanum. In the upper cornice west run, the very small blocks U74A and U54A were undoubtedly put in as shims to fill cracks that opened during the initial period of construction and deformation. They look to be pieces removed from the straight ends of larger blocks.

33 I can find no consistent pattern in the placement of particularly small blocks in the exedrae; in the west gallery exedrae, short blocks are placed toward the ends of the curves, near the piers, whereas in the east gallery exedrae, a short block is placed in the center of the curve. Again, in the upper cornice, the block dimensions are more consistent.

There are good reasons to agree with Mainstone that the cornice blocks were cramped together with iron under the bearing masonry.[34] First, there is the analogy to the sixth-century buildings just considered. The Hagia Sophia cornices would have been designed and built to act as tensile chains within the structure of the building. Second, there is also at least one iron cramp visible under the masonry, on the upper cornice behind the block U31–U32 joint.[35] Third, the pattern of distortion in Hagia Sophia indicates the presence of chains in the structure at the two cornice levels capable of exerting at least some influence on the structure during initial construction.[36] Finally, the structural history of the building shows that the nave cornices were treated by the architects as important leveling, chaining, and springing courses. The builders took care to cushion the weight of masonry bearing on the cornices by putting sheets of lead under them at crucial points in the structure.[37] Generations of architects, meanwhile, added the elaborate network of visible iron ties to strengthen the cornice levels in attempts to absorb the outward thrusts of the vaulting.[38]

Clearly, then, the Hagia Sophia nave cornices were crucial elements in the structural design of the Great Church, intended to serve as leveling courses, firm foundations for the springing of the vaults, and tensile chains. A natural outgrowth of local building practice based on centuries of experience, they represent the structural sophistication of Justinianic architects faced with the need to contain the thrusts of enormous vaulted structures. While earlier structures, such Hagios Polyeuktos and Hagioi Sergios and Bakchos, were rather tentative in their organization of tensile structure, Hagia Sophia, Philippi Basilica B, and possibly Ephesos St. John show this system of two-story vaulted building in its mature form. Whether such tensile chaining could be effective in containing the forces of a structure this size is a different question.[39] The important point for the history of structural design is that the attempt was made in all the great Justinianic structures.

34 See note 8.

35 Mainstone found it to be 30 mm square, lying 50 mm behind the face of the sixth-century brickwork (*Hagia Sophia*, 77, visible in plate 93). Mr. Van Nice kindly brought this cramp to my attention.

36 These distortions of the vertical piers were made clear by Van Nice's survey and can be verified by any observant visitor. According to Mainstone, the outward lean begins well below the level of the gallery, but at that level it increases threefold to ca. 3 cm for every 1 m rise (Mainstone, "Tympana," 357–8). For Mainstone's analysis of the structural deformations, see his *Hagia Sophia*, 87–9, esp. figs. 105 and 119. From Van Nice's plates, it seems clear that lean of the great arches becomes more extreme immediately above the level of the upper cornice (Van Nice, *Saint Sophia*, particularly the transverse section, plate 29, and the superimposed trace plans on plate 44).

37 The use of the lead in the piers is described, after a fashion, by Procopius, *The Buildings*, I.i. 53. W. Emerson and R. Van Nice, "Hagia Sophia: Collapse of the First Dome," *Archaeology* 4, no. 2 (1951), 101, note a visible 9-mm-thick sheet of lead extending through the southeast pier at the springing level, and lead used elsewhere in corresponding locations and in the ground-level springing of the buttress piers. Also noted by Mainstone, *Hagia Sophia*, 186.

38 On the addition of iron ties see Mainstone, *Hagia Sophia*, 63, 70–1, 82–3, 108–9, fig. 77, and plans A2–A4, A9, A10. Also see the drawings in his "Tympana," 353–68. For his analysis of tensile tie strength and effectiveness, 167.

39 Discussed in ibid., 167.

Indications of the Construction Sequence at Hagia Sophia

Despite the homogeneity of the cornices, there are distinct breaks between the piers and the straight north and south runs. These are caused by the sequence of construction and by the rebuilding of the tympana at a later date (Figures 42 and 43). Furthermore, the initial distortions during construction, most notably the spreading of the four great piers, presumably caused the cracking on the upper cornice, so broad as to require the insertion of wedges, blocks U47A and U54A, at the western corners. Enormous gaps in the masonry joints are still visible in the upper cornice exedrae, where iron ties have been put in to consolidate the masonry, and at the joints at the ends of the rebuilt upper cornices.

Surface Tooling

Indications of tooling to smooth the exposed upper surfaces of the cornices yield valuable information on the construction of the building (Figures 42 and 43). As my model, I am following Emerson and Van Nice's analysis of the dome cornice surface tooling, which allowed them to identify and date repairs of the great dome.[40]

Three distinct types of tooled surface are discernible on the nave cornices, representing stages in the finishing of Proconnesian marble.[41] The roughest, an irregular surface showing gouges and protrusions, represents the "quarry state," in which the block was dressed for shipment by a scabbling pick after gross protrusions were knocked off with a splitter and mallet. This stage is rarely seen on the gallery cornice, but is common on the upper cornice.[42] Most of the gallery-level blocks along the colonnades and exedrae have a surface made smoother with strokes of a single point and mallet.[43] On the upper cornice, however, only the exedrae east of the main piers are well and evenly tooled with the point. Along the walls, blocks typically show a mixture of quarry state and point marking, giving the impression of a hasty job.[44] Some gallery blocks such as G50, primarily in the piers and west gallery,

40 Emerson and Van Nice found the same variety of surfaces on the dome cornice, which, "being invisible from every other part of the building, was not originally tooled to an anonymous mirror polished surface" ("Hagia Sophia," 425). All the sixth-century segments were finished with the five-clawed chisel and marked with a setting line. The western, tenth-century work reused these claw-chiseled pieces mixed with others tooled with a broad chisel. The fourteenth-century repair to the eastern segment used irregular stones, some point-marked, some polished smooth, and some rough but for a polished band at one end (ibid., 425–6).

41 See N. Asgari, "Roman and Early Byzantine Marble Quarters of Proconnesus," *Proceedings of the Xth International Congress of Classical Archaeology* (Ankara, 1978), 1: 467–80, particularly 475–8. Asgari's photo, of an unfinished sarcophagus on Proconnesus, plate 40, fig. 11, clearly shows the three main stages of tooling: pick-marked on the roof, point-marked on the gable wall, and claw-chiseled to a sharp angle on the ridge of the roof and the four corners of the chest.

42 Ibid., 475–6; seen, e.g., on G5 and G61 on the gallery cornice. On the upper cornice, blocks U47A, U47, and U48 appear never to have been smoothed at all. Only in rare instances, as on the point of U44, is this unfinished quarry state seen on the undersurface of a cornice block.

43 Typical point-marked blocks include G14 and G66. In rare places, primarily on G18 and G75, one may see protruding masses of rough-scabbled stone partially removed by the point.

44 Several rows of blocks – U16 to U19 or U26 and U27, for instance – appear to have been smoothed with the point for only two-thirds of their width, along the nave side, while the strip along the wall was left rougher. Several blocks, such as U15 and U50, have more prominent outcropping masses of unsmoothed scabbling.

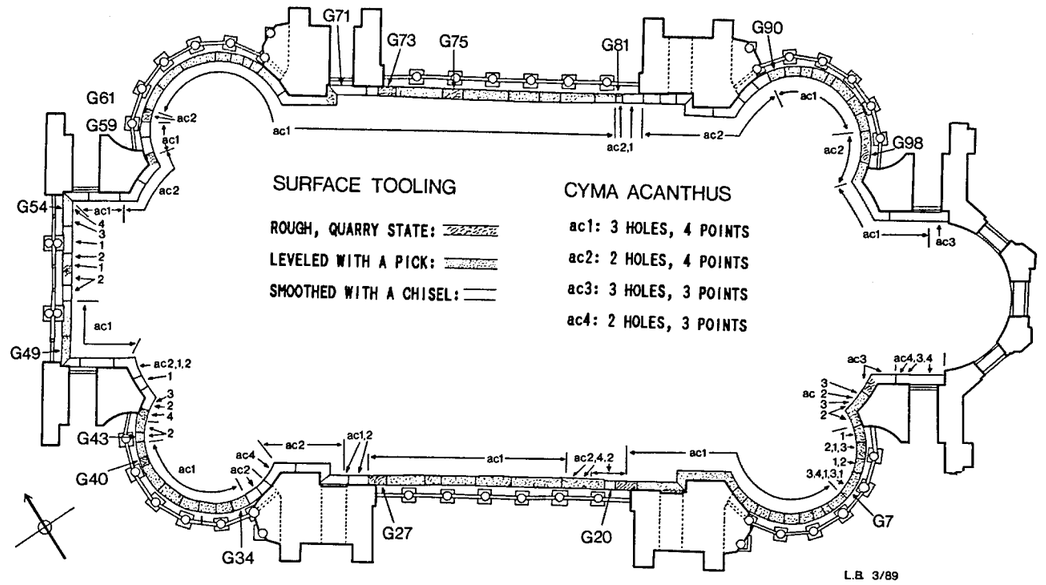

Fig. 42. Gallery cornice: patterns of surface tooling and cyma acanthus distribution.

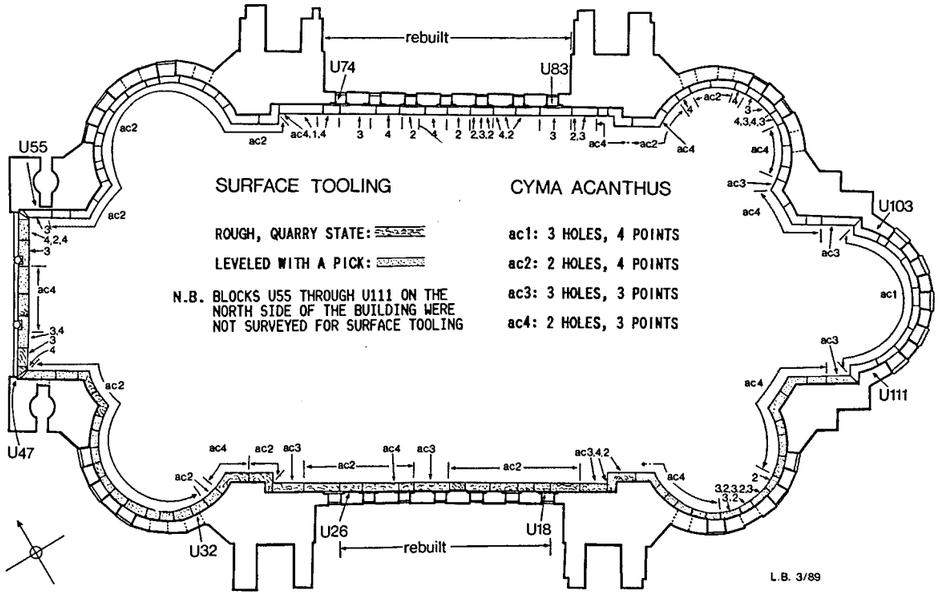

Fig. 43. Upper cornice; patterns of surface tooling and cyma acanthus distribution.

were tooled to a smoother finish with a five-toothed claw chisel, resulting in a pattern of radical or crosswise strokes, depending on the habit of the individual mason. The varied treatment of several blocks, such as G79, G80, and G99, makes clear that all of these had been through the point-marked stage before further smoothing with the claw chisel. Finally, a few blocks, such as G47, are smooth without visible tool marks, perhaps finished with the flat chisel and mallet. No upper cornice blocks had been completely smoothed with either clawed or flat chisel.[45]

Careful scrutiny of the nave cornices' surface tooling leads to five observations that bear on the history of the building's construction. First, the gallery-level pier and arcade blocks appear to have been tooled in separate operations. All of the cornice blocks in the main and subsidiary piers, except for the southeast subsidiary pier, were carefully smoothed with a claw chisel, even though most of their surfaces are invisible from the galleries, hidden by the bulk of the bearing masonry except where the tunnel vaults once penetrated. Cornice blocks in the arcades and exedrae, however, though visible from the galleries, were smoothed only with the point and mallet. A definite change in treatment is visible at the joints closest to the pier edges.[46] We will see the same divisions in the carving of the cyma acanthus.

Second, any surface tooling beyond the roughest pick-marked stage appears to have been done in situ, after the placement of the blocks. Several observations suggest this. In a number of places on both cornices, the final tooling is carried back only to the edge of the bearing masonry, reflecting its irregularities of shape. While this could conceivably have been planned and executed on the ground, it seems unlikely, since areas of irregular shape continue across adjacent blocks within larger sections.[47] Again, the situation is analogous to the carving of the cyma acanthus.

Third, the difference in tooling between the gallery and upper cornice surfaces indicates increasing haste as the building progressed, something noted by other observers.[48] Assuming the pier blocks of the gallery cornice were finished before those of the infilling arcades, this also explains why the less visible pier cornice blocks were more carefully tooled than the others. Masses of quarry-state, barely leveled stone, small and rare on the gallery level, commonly protrude from the surface of the upper cornice, making the already narrow walkway more treacherous. That this was not considered ideal may be inferred from the careful finishing of the sixth-century segments of the cornice of the second dome.

Since the tooling of the upper cornice is less regular and less careful, it is

45 However, I was not able to survey the surfaces of blocks U55 through U111 for surface tooling, due to dangerous conditions on the north and apse sections of the upper cornice.

46 Only in one such location, at the east end of the north arcade, was the transition from the smooth chiseled northeast pier to the point-marked arcade obscured by a zone of claw chiseling on blocks G79 to G82, broadening from the lip as one moves to the east. On block G99, in the northeast subsidiary pier, the change occurs at the western angle of the block; the northernmost end was left point-marked, while the adjacent pier block, G98, continued this surface and was left rough at its junction with the first exedra block, G97. The southeast subsidiary pier and west arcades present special problems, which will be considered presently.

47 Smoothed patches run from G79 to G82 for instance, and unsmoothed masses from U15 to U19 or U47 to U48.

48 Emerson and Van Nice ("Hagia Sophia," 419–20) and Mainstone (*Hagia Sophia,* 198) attribute increasingly rapid construction above the gallery level to increased confidence as well as to the need for speed. Mainstone notes signs of speed, even of sloppiness, in the finishing of other carved marblework in the building (*Hagia Sophia,* 213).

harder to draw specific conclusions from it. Surface treatment varies from section to section and block to block, but does not indicate a clear division between pier blocks and wall blocks. Only the apse cornice, U103 through U111, is distinctly separate in its workmanship. In a reverse of the situation below, the pier blocks seem less commonly smoothed with the point than do the exedra blocks and western run.[49]

This suggested sequence of construction and finishing of the cornices is reflected in the sequence and distribution of carved motifs on the undersurfaces. There are similarities between the surface tooling procedure and another repetitious large-scale operation, the carving of the acanthus leaves on the cyma recta. I have identified four major types of acanthus leaf used on the cyma, based on the number of points and lobes, and used these as the basis of my analysis. Individual masons presumably used their own favorite variants of the design, and thus the pattern of distribution shows several things about workshop procedure. The sculptural evidence suggests that four teams carried out most of the cyma acanthus and modillion carving, probably in that order, in serial production, each working on a long stretch or a single exedra. Working procedures of the Hagia Sophia sculpture atelier were like those of Byzantine brick masons. Dimensions were flexible and solutions were ad hoc, with more concern for broad results than for absolute uniformity of details. In general only one type of leaf is used per block. The exceptions – blocks with odd or multiple leaf types – occur in areas that seem to have been saved for last and finished in a hurry, usually at the end of homogeneous stretches.[50]

By correlating the distribution of carved acanthus types with patterns of surface tooling, one learns more about the sequence of construction.[51] In general, the piers and the western exedrae display uniform stretches of cyma acanthus (Figures 42 and 43). The north and south straight runs are uniform on the gallery level, but quite varied on the upper cornice. One, and possibly two, areas of the gallery cornice stand out as exceptional. The blocks of the southeast subsidiary pier and its exedra, from the angle of G2 to the north edge of G6, exhibit a much greater than usual surface irregularity. This was the only significant stretch of the gallery cornice left rough, smoothed only at the lip. This area also displays the most jumbled series of cyma acanthus, the leaf pattern changing no less than five times on G7 alone. The best explanation is that this area was left to the last, and then finished by all available hands in a rush.[52] Anomalies of this sort on both gallery and upper cornices

49 The surfaces of the cornice blocks below the north and south tympana are highly irregular, with most of them point-marked, some, such as U22 and U27, left quite rough, and some, from U16 to U19, partially worked with the point. Surface conditions on the apse blocks were noted from the vantage point of the U1 pier.

50 Block G21 has a variant type of leaf at the cracked place on the block, as if that spot were left for someone else to deal with. Extremely broad leaves are seen in only a few places, on isolated blocks: G10 and G11, G91, and parts of G24 and U111. Each of these places marks the end of a homogeneous stretch; my guess is that they were left for last and finished in a hurry by using fewer, broader leaves than normal.

51 I am not considering the evidence of the more than two hundred masons' marks visible on the cornice. Although important keys to understanding the sculpture and workshop practice, they lie beyond the scope of this discussion of design and construction. For the masons' marks, see the author's dissertation, chaps. 7 and 8.

52 The jumbled sequences and unusual surfaces are most pronounced on blocks G5 through G7 and U6 and U7. The only other gallery stretch so unpredictable in its cyma carving is along the west arcade, especially from G51 to G54. The surface here is uneven, but that seems due more to

in the southeast exedra support Mainstone's suggestion, based on peculiarities of vaulting, that the southeast exedra served as a staging area for the builders.[53] Another possible staging area is the west gallery, since cornices at both levels there show the same multiplicity of carving, while the upper surfaces of some of the blocks were left in quarry state.

The cornices were carved almost entirely on the ground, with only the upper surface tooling and sculpture at the ends of the blocks left to be finished after they were hoisted into place.[54] Since they were integral to the great piers and thus had to be set in place long before the infilling arcades, preparing them must have been a priority early in the project. The gallery cornice was carefully finished on both under and upper surfaces; but as we have seen, the less visible upper cornice was more hastily finished, probably under pressure from an impatient emperor. At least by the time the great piers reached the upper cornice level, the need for the elements of the infilling arcades and vaults would have become crucial, so all of the leading masters may have been set to work on the remaining gallery cornice blocks. The only consistently high-quality carving on the upper cornice occurs in the apse; this, combined with the evidence of breaks noted in Figure 42, indicates that special care was taken with this most important part of the church.

In Mainstone's recent study of Hagia Sophia, he proposes a time line for the initial construction, assuming the building was complete at the time of its dedication in 537.[55] He assigns the construction of the gallery cornice to a period about two years into the project, and the upper cornice, capping the piers and galleries, to about a year later; hence, the cornices would have been essentially complete halfway through the building campaign. I would like to emphasize that it seems from my evidence that a major structural break occurs between the piers and the arcades at the lower cornice level; it seems clear that the infilling arcades did not keep pace with the pier construction.[56] On the contrary, there may well have been a delay in the procurement or preparation of such great columns, and this may be the cause of the break. The same breaks are not so apparent at the upper cornice level; however, the evidence of the unfinished pilasters by the Emperor Alexander mosaic shows that again the pier construction preceded and outran the work on the infilling arcades.[57]

multiple beam emplacement scars than to careless tooling, though a rough patch on G52 is difficult to explain in such an exposed place.

53 Mainstone, *Hagia Sophia,* 200.

54 Harrison (*Temple for Byzantium,* 80–1) comes to a different conclusion regarding the carving at Hagios Polyeuktos, which he believes was done almost entirely after the blocks were hoisted into place. His argument is based on a pilaster capital face (*Temple for Byzantium,* Fig. 85) that was unfinished where it abutted the wall. I have presented my arguments for the Hagia Sophia cornices as having been carved on the ground, with only the ends of long runs left to be carved in situ, in my dissertation (112–13) and in a paper ("Architectural Sculpture in Hagia Sophia: Some Considerations of Style, Motifs, and Workshop Practice," College Art Association Annual Meeting, San Francisco, February 1989). My argument is based on the nature and distribution of mismatched joints and unfinished areas on the sculpted undersurfaces.

55 Mainstone, *Hagia Sophia,* 185–200 and fig. 212.

56 As Mainstone notes (ibid., 190, 200), the piers and their great connecting arches were the priority, and the infilling aisle and gallery vaults could wait.

57 Ibid., 191–3. This sequence of building changes and reconstructions was first demonstrated by P. A. Underwood and E. J. W. Hawkins, "The Mosaics of Hagia Sophia at Instanbul: The Portrait of the Emperor Alexander," *Dumbarton Oaks Papers* 15 (1961), 187–217.

Holes and Emplacement Scars

The nave cornices provide one final sort of evidence concerning the early history of the building, which I shall touch on briefly. A great number of holes and craters can be distinguished on the upper surfaces of both cornices. Most, though not all, are visible in Van Nice's plates.[58] On the gallery cornice at least, most can be assigned to distinct series, and their original functions can be guessed.

First, and most important, are the two series or large craters on the upper surface of the gallery cornice (Figure 44). These prominent features, visible in Van Nice's gallery cornice plans and my photograph, were lamp beam emplacements. A few of the beams are still in place, allowing us to visualize the cornices' nonstructural function as a lamplighters' walk (Figure 45). Following these craters around the gallery cornice, one can reconstruct two series of lamp beams, about one hundred in each series, corresponding closely to the elevation of the nave (Figure 46). Although I have no hard evidence of their early date, they do resemble similar scars in the other great Justinianic buildings and in no way contradict descriptions by Byzantine authors.[59]

Along the nave edge of the gallery cornice runs a series of smaller holes on regular 58- to 60-cm centers, 8 to 11 cm back from the edge.[60] These are presumably the anchors for the balustrade that predated the current wooden one erected by Fossati in the mid-nineteenth century. We have several views of the previous balustrade, by Grélot and Fossati.[61] Numerous small scars are visible on the surface of the upper cornice as well, but the extreme structural distortions, necessitating bracing and even reconstruction, have muddied the evidence. Further close study will be required to decipher their pattern and function.

Conclusion

My aim in studying the Hagia Sophia cornices has been to move beyond stylistic analysis in the study of architectural sculpture. Through close visual examination, and the correlation of various types of evidence, I have tried to understand the production of the cornices, their role in the structure of the Great Church, and their bearing on other questions involving Justinianic architecture. Many of the suggestions put forward in this study are only that,

58 See Van Nice, *Saint Sophia,* plates 2 and 17–19 for the gallery cornice plans; and plates 3 and 21–3 for the upper cornice.

59 Paul the Silentiary's poetic description is the best known (*Descriptio S. Sophiae,* ll. 806–70). Mainstone (*Hagia Sophia,* 126) interprets the passage very differently, seeing the lamps described as hanging from the iron tie rods. One is also struck by the description of Justinian's gift of lamps from the anonymous eighth- or ninth-century author of the *Narratio de S. Sophia* (para. 24). For both passages, see C. A. Mango, *The Art of the Byzantine Empire, 312–1453: Sources and Documents* (Englewood Cliffs, N.J., 1972).

60 Each measures from 6×7 to 6×12 cm, with the long axis parallel to the cornice edge. The few that can be measured are about 5 cm deep, but most are filled with a metal (lead?) plug and were further camouflaged at a later date with a fibrous fill or a layer of gray-painted red putty.

61 G. J. Grélot, *Relation nouvelle d'un voyage de Constantinople* (Paris, 1680), the interior view on p. 158 (where the balustrades are marked "H"); G. Fossati, *Aya Sofia, Constantinople* (London, 1852), plate 24.

in the southeast exedra support Mainstone's suggestion, based on peculiarities of vaulting, that the southeast exedra served as a staging area for the builders.[53] Another possible staging area is the west gallery, since cornices at both levels there show the same multiplicity of carving, while the upper surfaces of some of the blocks were left in quarry state.

The cornices were carved almost entirely on the ground, with only the upper surface tooling and sculpture at the ends of the blocks left to be finished after they were hoisted into place.[54] Since they were integral to the great piers and thus had to be set in place long before the infilling arcades, preparing them must have been a priority early in the project. The gallery cornice was carefully finished on both under and upper surfaces; but as we have seen, the less visible upper cornice was more hastily finished, probably under pressure from an impatient emperor. At least by the time the great piers reached the upper cornice level, the need for the elements of the infilling arcades and vaults would have become crucial, so all of the leading masters may have been set to work on the remaining gallery cornice blocks. The only consistently high-quality carving on the upper cornice occurs in the apse; this, combined with the evidence of breaks noted in Figure 42, indicates that special care was taken with this most important part of the church.

In Mainstone's recent study of Hagia Sophia, he proposes a time line for the initial construction, assuming the building was complete at the time of its dedication in 537.[55] He assigns the construction of the gallery cornice to a period about two years into the project, and the upper cornice, capping the piers and galleries, to about a year later; hence, the cornices would have been essentially complete halfway through the building campaign. I would like to emphasize that it seems from my evidence that a major structural break occurs between the piers and the arcades at the lower cornice level; it seems clear that the infilling arcades did not keep pace with the pier construction.[56] On the contrary, there may well have been a delay in the procurement or preparation of such great columns, and this may be the cause of the break. The same breaks are not so apparent at the upper cornice level; however, the evidence of the unfinished pilasters by the Emperor Alexander mosaic shows that again the pier construction preceded and outran the work on the infilling arcades.[57]

multiple beam emplacement scars than to careless tooling, though a rough patch on G52 is difficult to explain in such an exposed place.

53 Mainstone, *Hagia Sophia*, 200.

54 Harrison (*Temple for Byzantium*, 80–1) comes to a different conclusion regarding the carving at Hagios Polyeuktos, which he believes was done almost entirely after the blocks were hoisted into place. His argument is based on a pilaster capital face (*Temple for Byzantium*, Fig. 85) that was unfinished where it abutted the wall. I have presented my arguments for the Hagia Sophia cornices as having been carved on the ground, with only the ends of long runs left to be carved in situ, in my dissertation (112–13) and in a paper ("Architectural Sculpture in Hagia Sophia: Some Considerations of Style, Motifs, and Workshop Practice," College Art Association Annual Meeting, San Francisco, February 1989). My argument is based on the nature and distribution of mismatched joints and unfinished areas on the sculpted undersurfaces.

55 Mainstone, *Hagia Sophia*, 185–200 and fig. 212.

56 As Mainstone notes (ibid., 190, 200), the piers and their great connecting arches were the priority, and the infilling aisle and gallery vaults could wait.

57 Ibid., 191–3. This sequence of building changes and reconstructions was first demonstrated by P. A. Underwood and E. J. W. Hawkins, "The Mosaics of Hagia Sophia at Instanbul: The Portrait of the Emperor Alexander," *Dumbarton Oaks Papers* 15 (1961), 187–217.

Holes and Emplacement Scars

The nave cornices provide one final sort of evidence concerning the early history of the building, which I shall touch on briefly. A great number of holes and craters can be distinguished on the upper surfaces of both cornices. Most, though not all, are visible in Van Nice's plates.[58] On the gallery cornice at least, most can be assigned to distinct series, and their original functions can be guessed.

First, and most important, are the two series or large craters on the upper surface of the gallery cornice (Figure 44). These prominent features, visible in Van Nice's gallery cornice plans and my photograph, were lamp beam emplacements. A few of the beams are still in place, allowing us to visualize the cornices' nonstructural function as a lamplighters' walk (Figure 45). Following these craters around the gallery cornice, one can reconstruct two series of lamp beams, about one hundred in each series, corresponding closely to the elevation of the nave (Figure 46). Although I have no hard evidence of their early date, they do resemble similar scars in the other great Justinianic buildings and in no way contradict descriptions by Byzantine authors.[59]

Along the nave edge of the gallery cornice runs a series of smaller holes on regular 58- to 60-cm centers, 8 to 11 cm back from the edge.[60] These are presumably the anchors for the balustrade that predated the current wooden one erected by Fossati in the mid-nineteenth century. We have several views of the previous balustrade, by Grélot and Fossati.[61] Numerous small scars are visible on the surface of the upper cornice as well, but the extreme structural distortions, necessitating bracing and even reconstruction, have muddied the evidence. Further close study will be required to decipher their pattern and function.

Conclusion

My aim in studying the Hagia Sophia cornices has been to move beyond stylistic analysis in the study of architectural sculpture. Through close visual examination, and the correlation of various types of evidence, I have tried to understand the production of the cornices, their role in the structure of the Great Church, and their bearing on other questions involving Justinianic architecture. Many of the suggestions put forward in this study are only that,

58 See Van Nice, *Saint Sophia*, plates 2 and 17–19 for the gallery cornice plans; and plates 3 and 21–3 for the upper cornice.

59 Paul the Silentiary's poetic description is the best known (*Descriptio S. Sophiae*, ll. 806–70). Mainstone (*Hagia Sophia*, 126) interprets the passage very differently, seeing the lamps described as hanging from the iron tie rods. One is also struck by the description of Justinian's gift of lamps from the anonymous eighth- or ninth-century author of the *Narratio de S. Sophia* (para. 24). For both passages, see C. A. Mango, *The Art of the Byzantine Empire, 312–1453: Sources and Documents* (Englewood Cliffs, N.J., 1972).

60 Each measures from 6×7 to 6×12 cm, with the long axis parallel to the cornice edge. The few that can be measured are about 5 cm deep, but most are filled with a metal (lead?) plug and were further camouflaged at a later date with a fibrous fill or a layer of gray-painted red putty.

61 G. J. Grélot, *Relation nouvelle d'un voyage de Constantinople* (Paris, 1680), the interior view on p. 158 (where the balustrades are marked "H"); G. Fossati, *Aya Sofia, Constantinople* (London, 1852), plate 24.

Fig. 44. Surface of gallery cornice block G51, showing lamp beam emplacement scars. (Photo: author)

Fig. 45. Surface of gallery cornice block G46, showing existing lamp beam and its attachment. (Photo: author)

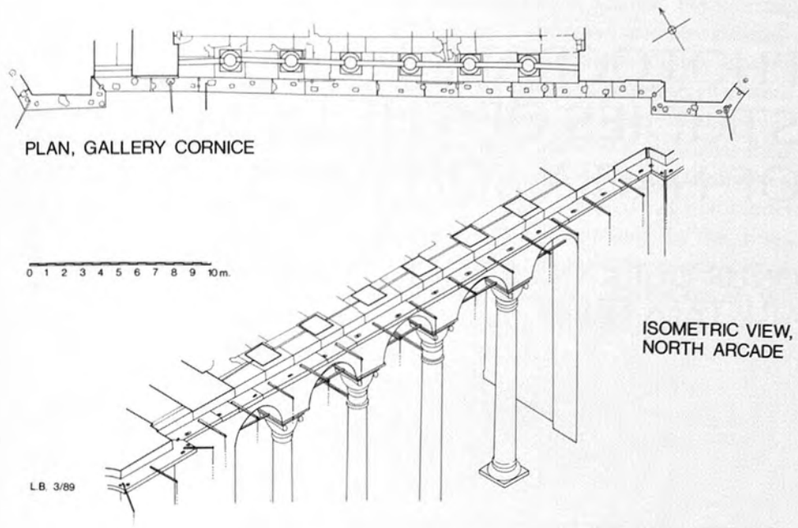

Fig. 46. Lamp emplacement. Plan, gallery cornice showing series A and B holes on blocks G70 to G87. (After Van Nice, plate 18) Isometric view, north arcade, showing series A lamp beams (reconstructed) and series B anchors. (After Van Nice, plate 44)

based on limited data, and must be tested with more material. It seems to me that, if we are to get beyond Choisy and Ward-Perkins, more comparative studies on structural elements are needed – the construction of Hagia Sophia hardly occurred in a vacuum. Good, thorough structural surveys of such major buildings as the Stoudion Basilica and Hagioi Sergios and Bakchos are still lacking.

PHOTOGRAMMETRIC STUDIES OF THE DOME OF HAGIA SOPHIA

ONUR GÜRKAN, SERHAT CAMLIDERE, AND MUSTAFA ERDIK

A series of geodetic studies is planned to provide three-dimensional data (e.g., shapes, dimensions, relative position, and deformation) for some of the major structural elements of the Hagia Sophia. The information gained from such studies should be of value for many facets of historical investigation, including efforts to resolve the theoretical underpinning of the original design scheme, as well as methods applied to, difficulties encountered in, and solutions found before, during, and after the original construction and/or reconstructions of the building structure. Accordingly, data acquisition and analysis should be performed with a high degree of precision.

Two types of survey are to be undertaken. The first will be a survey of selected building elements (e.g., domes, arches, and main walls) to determine their present configuration, dimensions, and relative position in three dimensions. The second will be aimed at detecting and monitoring natural oscillations and undesirable displacements at predetermined critical points. This brief essay describes initial geodetic measurements of the first type, derived from overlapped photographs of the underside of the main dome taken on glass plates by a terrestrial camera and applying the principles of close-range photogrammetry. As such, it represents only a prelude to the extensive program of photogrammetric investigations planned for the building.

Data Acquisition

Photographs of the inside surface of the main dome from two ground points, taken by a member of the Department of Photogrammetry of Yıldız University using a Carl Zeiss Jena UMK 10/1318 terrestrial camera (dated 1984), provided three-dimensional digital object data. A microgeodetic network

The authors thank Professor A. Alk of Yıldız University, Istanbul, for providing the photographs of the dome and Mr. H. Altan for generously permitting us to use the EGHAS program.

consisting of four points on the floor was established. On the basis of the measurement of angles, distances, and elevation differences made by a theodolite, and applying a least-squares adjustment for the redundant observations, the rectangular X, Y, Z coordinates of network points in an arbitrary system were established. Making use of this reference frame, we observed six points at the base and one point at the apex of the main dome and calculated their relative coordinates by the spatial intersection method. Considering these seven points as control points and using the photo pair, we created a spatial model of the main dome utilizing an analytical plotting instrument. In this way, X, Y, Z rectangular coordinates of 1,115 sample points on the inside surface of the dome were measured. These sample points were selected so that the forty ribs of the dome could be represented in the process of creating a digital terrain model (DTM) of the dome.

Data Verification

The DTM of the dome of Hagia Sophia was created using the computer program entitled EGHAS (H. Altan, Graftek Inc.). This program was developed especially for topographic mapping from a random data set and requires the verification of the data in creating the DTM of the dome. For this purpose the output data from the analytical plotting instrument were fed as input data for the program. The program generated triangles by the Delaunay triangulation method[1] for the construction of contour lines by cubic splines. During the verification of automatically generated triangles, some were found to be inconsistent, and we changed the X, Y coordinates by a few centimeters, rejected points, or added points. In the end, the original coordinates of fifteen points were changed (by a maximum of 3 cm), two were rejected, and four were added. Figure 47 shows a perspective view of the network utilized; Figure 48 shows a contour map of the inside surface of the main dome with the ribs included. The contour lines were generated from verified digital data utilizing cubic spline functions in the interpolation of the data. The contour map depicted in Figure 49 refers to the inside surface of the dome after the removal of the ribs. In this figure a total of 603 points were used for mapping.

Best-Fitting Spherical Section

The data with the ribs removed can be used to assess the parameters of the best-fitting spherical section. The X, Y, Z coordinates of the center of the sphere and the radius are determined through a weighted least-squares minimization of the differences between the observed and predicted displacements at the data points.[2] For this purpose, the following equation was considered:

1 See, e.g., M. J. McCullagh and C. G. Ross, "Delaunay Triangulation of a Random Data Set for Isarithmic Mapping," *Cartographic Journal* 17, no. 2 (1980), 93–9.
2 E. M. Mikhail, *Observations and Least Squares*. New York, 1976.

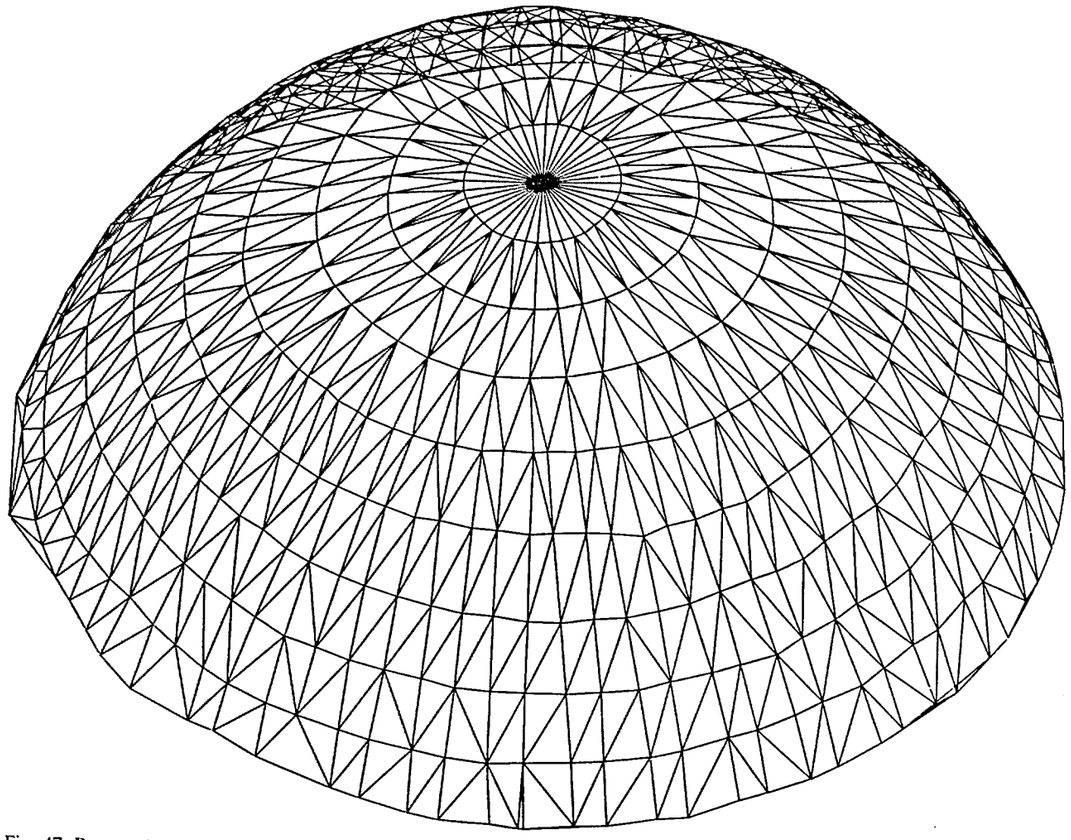

Fig. 47. Perspective view of triangles formed from 603 sample points (ribs excluded).

$$\mathbf{r}_i + \mathbf{v}_i - \mathbf{r}_0 = R, \quad i = 1, 2, \ldots, 603,$$

where

$\mathbf{r}_i = [X_i, Y_i, Z_i]$, the position vector of a sample point;
$\mathbf{v}_i = [Vx_i\ Vy_i, Vz_i]$, the radial deviation vector of a sample point from the best-fitting sphere;
$\mathbf{r}_0 = [X_0, Y_0, Z_0]$, the position vector of the center of the best-fitting sphere;
$R =$ the radius of the best-fitting sphere.

The unknown quantities, measured from the reference coordinate point, and their standard deviations were found to be as follows:

$X_0 = 968.724 \pm 0.010$ m,
$Y_0 = 1{,}010.829 \pm 0.010$ m,
$Z_0 = 158.695 \pm 0.024$ m,
$R_0 = 16.926 \pm 0.017$ m.

A graphic representation of the radial deviation $\mathbf{v}_i$ is provided in Figure 50 as a contour map.

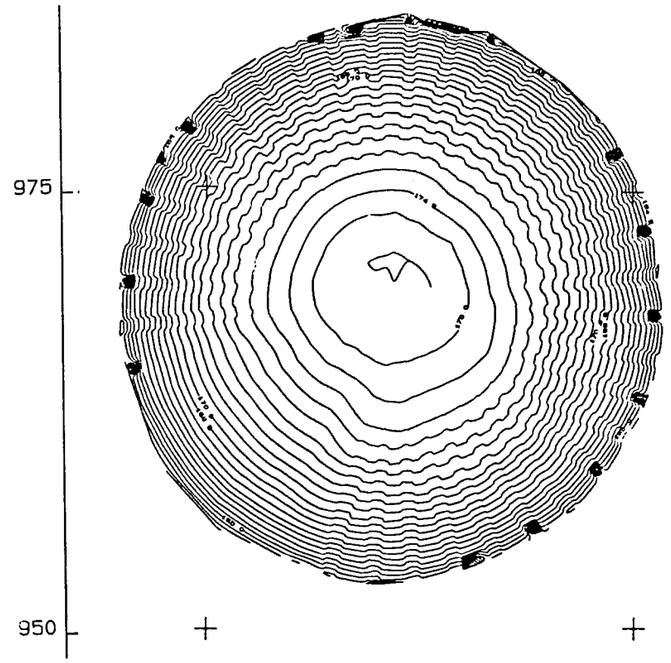

Fig. 48. Contour map of the inside of the dome, including ribs.

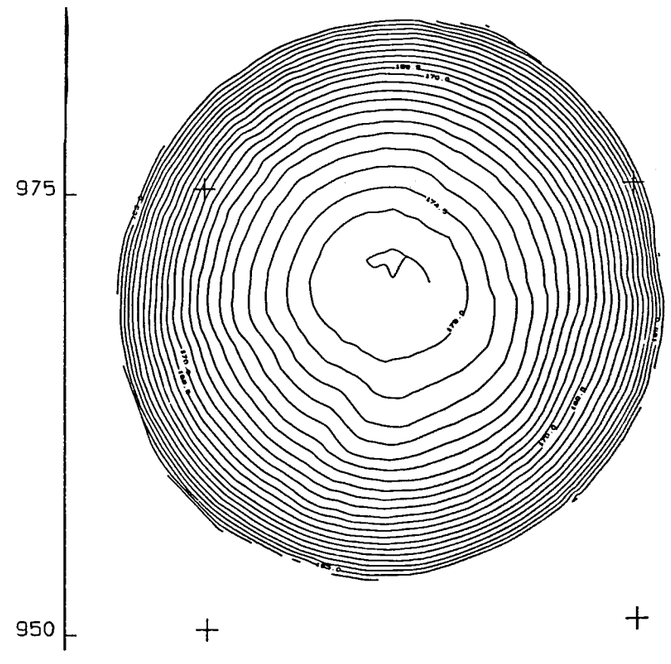

Fig. 49. Contour map of the inside of the dome, excluding ribs.

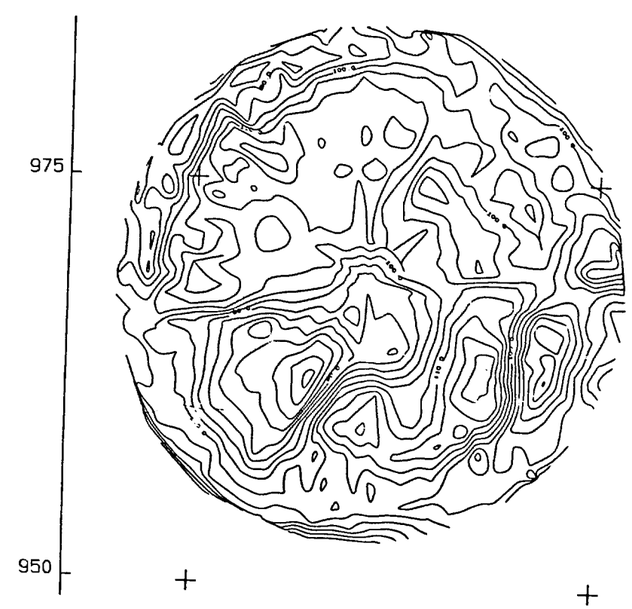

Fig. 50. Contour map of radial deviation v_i.

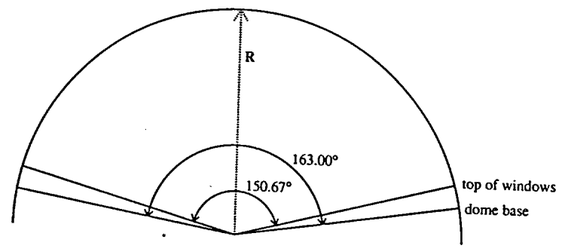

Fig. 51. Segment angle from the top of the windows and from the dome base; R is the radius of the best-fitting sphere.

Conclusion

We have presented an introductory example of the measurement and modeling of a single component of Hagia Sophia's structure. The study is an embryonic one, illustrating a new avenue of interpretation for the state of Hagia Sophia, yet the findings warrant the following conclusions: (a) The radius of the best-fitting sphere is 16.93 ± 0.02 m. The segment angle is 150.67 degrees from the top of windows and 163.00 degrees from the base of the dome (Figure 51). (b) The amount of deviation in the actual inner dome surface from the best-fitting sphere varies from -42 to $+27$ cm. (c) The lines observed separating the segments of the dome with different contour map characteristics can be correlated with different segmental reconstructions of the dome.

THE STRUCTURE OF HAGIA SOPHIA IN THESSALONIKI FROM ITS CONSTRUCTION TO THE PRESENT

KALLIOPE THEOCHARIDOU

In terms of both architectural conception and physical size, the church of Hagia Sophia in Thessaloniki represents the closest building on Greek territory to the Great Church of Constantinople. It was in fact the first large, domed Byzantine church to introduce into Thessaloniki, the capital of East Illyricum, the new concepts in ecclesiastical architecture that were born in the age of Justinian. At the same time, it seems to be the last in a series of great monuments, for, in its own geographic area at least, it had no successor because of the difficult historical circumstances that arose after its construction. In its present form, the church is a ponderous, cube-shaped edifice, the body of which is more or less square in plan with a tripartite sanctuary projecting eastward from it. The basic interior dimensions are 30.92×28.90 m excluding the apse, or 30.92×40.06 m including the apse. The interior of the church has a cruciform nucleus, the center of which is covered by a large dome on pendentives, flanked by four barrel vaults. The average span of the barrel vaults is 10.16 m, but their length varies from 3.7 m (north and south arms) to 4.35 and 6.9 m (east and west arms, respectively). Lateral aisles and a narthex, with galleries above them, surround the nave on three sides.

The Structural History of the Church

In my study of Hagia Sophia I propose and support the theory that this domed church was built after the powerful earthquake that struck Thessaloniki at the beginning of the seventh century (in 618, according to recent theories). This earthquake is believed to have destroyed, among other large buildings in the city, the previous occupant of this site, a huge five-aisled basilica.[1]

The present church actually occupied the west half of the basilica's nave and inner aisles, and incorporated into its original design the previous struc-

1 K. Theocharidou, *The Architecture of Hagia Sophia, Thessaloniki* (Oxford, 1988), 10–13 (the basilica), 152–7 (dating).

ture's narthex, which probably survived the earthquake. This narthex, which served as the new church's exonarthex, no longer survives, but its existence can be posited from the presence of the basilica's foundations, which still project above floor level at the front of the church. Certain unusual arrangements and traces on Hagia Sophia's west facade, moreover, clearly indicate how the old narthex was attached to the new building.[2]

The church's present aspect is the result of six successive major building periods. Of these, the most important from a structural and statical point of view are the first and second, since they were the periods during which the building's basic structural system was created. The entire ground level and the cruciform center up to the base of the dome date from the first construction phase. The dome itself and its heavy, square base belong to the second period, as do the arcaded diaphragms at the ends of the north, south, and west arms of the cross at gallery level. The lower zone of the outer gallery walls belongs to the same period.

In its first phase, Hagia Sophia must have been designed to carry vaulted galleries, communicating visually with the cruciform nave through the wide, open arches at the ends of the arms of the cross. The central parts of the galleries would have been covered by rectangular cross-vaults on transversal arches, so that the arms of the cross were extended over the galleries as far as the facades, in a manner rather reminiscent of the external aspect of the church of St. Irene in Constantinople after it was remodeled in 740. This form of vaulted gallery may also account for the external buttresses on the north and south facades, which would not otherwise have been required.

The form and height of the outer gallery walls in the second period indicate that a low timber roof covered the galleries at that time, and so necessitated the construction of the arcaded tympana under the large open arches of the arms of the cross, in order to provide a support for this roof. These two successive construction periods were chronologically very close together. The first may be dated to just after the earthquake of 618, and the second to just after another earthquake, which occurred ca. 630, according to the most widely accepted opinion. This very short interval leaves open the possibility that the church's original dome and galleries were not in fact destroyed, but that the building might simply have been incomplete when the second earthquake struck the city, and it was afterward finished in a simpler way with timber-roofed galleries. All the later repairs and remodeling concerned the galleries and the attached annexes, and did not affect the basic structural system of the church.

An extensive early repair, dated to the eighth century, most probably after a fire had destroyed the south and west parts of the galleries and possibly the original mosaic decoration, repeated the architectural form of the second period. The center of the west gallery, however, remained uncovered. Around the middle of the tenth century, the west gallery was covered again in a normal manner and towers were added to its northwest and southwest corners. The towers were lost after the Turkish repairs and remodelings.

The changes made in the fourth phase, which is dated to the first half of

2 Ibid., 64–8 and figs. 22–3. The present discussion of the church's construction periods, their chronology, and the original and later forms of Hagia Sophia is based on the relevant chapters in this study.

the eleventh century, involved an increase in the height of the lateral galleries, so that the church acquired the more or less cubic shape it has today. During this period, the galleries became very important, in contrast to the early days, as is indicated by their elaborate decoration with frescoes and *opus sectile* floors.

Throughout these centuries, the two-story narthex of the earlier basilica was still standing in front of the west end of the domed church, functioning as an exonarthex at ground level and as a means of access to the galleries on the first floor. Only after the church had been converted to a mosque in 1524 was this structure demolished and replaced by an ordinary Ottoman portico. In the same period, the Ottoman tower, originally a minaret, was built outside the northwest corner of the church, simultaneously providing access to the galleries.

The Construction of the Church

Foundations

In view of the fact that our knowledge of Byzantine foundations is very limited, the case of Hagia Sophia could be considered one of the best-documented examples. Particularly since the excavations that took place in 1980–1 in the course of investigations for the restoration of the church, we are now able not only to reconstruct its system of foundations, along general lines, but also to make a complete and detailed presentation of certain foundation footings at specific points.[3] What makes the case of Hagia Sophia so interesting, however, is the way the Byzantine architect managed to cope with the existing foundations of the earlier basilica. His handling of the situation reveals both a conscious endeavor to create an independent foundation and an advanced knowledge of matters related to the task.

Materials and Methods of Construction

The foundations are constructed from undressed, green, local gneiss and an abundance of crushed-brick hydraulic mortar. No brick courses were used in the foundations, in contrast to the superstructure of the walls. In most places, the foundations of the new church were laid parallel to and in direct contact with the foundations of the previous basilica (Figure 52), and indeed are actually deeper than these. They reach a depth of 4.5 to 4.7 m below the present floor of the church, passing through an upper layer of artificial earth fill 4 m deep, and are finally embedded 0.5 to 0.7 m deep into a stiff, red, silty clay (Figure 53).

It is worth noting that the seventh-century architect avoided basing the new foundation on the water table, which occurs between the layer of earth fills and the red clay, a factor that the architect of the early Christian basilica

3 P. Astrinidou-Kotsaki and E. Stefanou-Katsanika, "Preliminary Observations on the Foundations and the Cracked Masonry of Hagia Sophia," in *Restoration of Byzantine and Post-Byzantine Monuments*, ed. K. Theocharidou and C. Mauropoulou (Thessaloniki, 1986), 91–7 and figs. 1–3. The excavations were carried out by the archaeologists S. Kissas and D. Nalbantis of the Ninth Ephorate of Byzantine Antiquities.

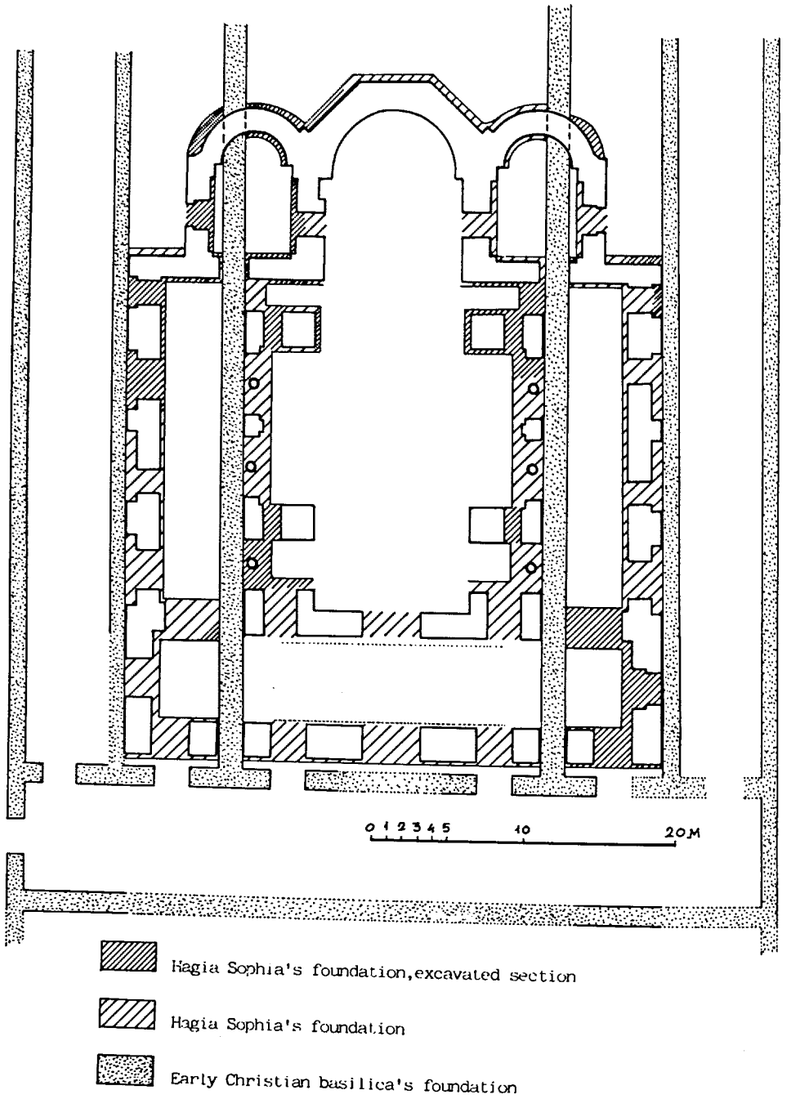
0 1 2 3 4 5 10 20M
Hagia Sophia's foundation, excavated section
Hagia Sophia's foundation
Early Christian basilica's foundation

Fig. 52. Hagia Sophia; plan of foundations.

did not take into consideration. Judging from the fact that the architect of the early Christian Acheiropoietos Basilica some 250 m farther north also based his structure just on the water table above the red clay,[4] the case of Hagia Sophia clearly illustrates a development in foundation techniques and understanding.

The footings were made thicker than the walls, usually by two successive

4 S. Tsotsos, T. Hatzigogos, N. Manou-Andreadis, K. Theocharidou, and V. Xantos, "Geotechnical Problems of the Foundations of Byzantine and Post-Byzantine Monuments in Thessaloniki, Greece," in *The Engineering Geology of Ancient Works, Monuments, and Historical Sites*, ed. George C. Koukis and Paul C. Marinos (Rotterdam, 1988), 487–94 and fig. 6.

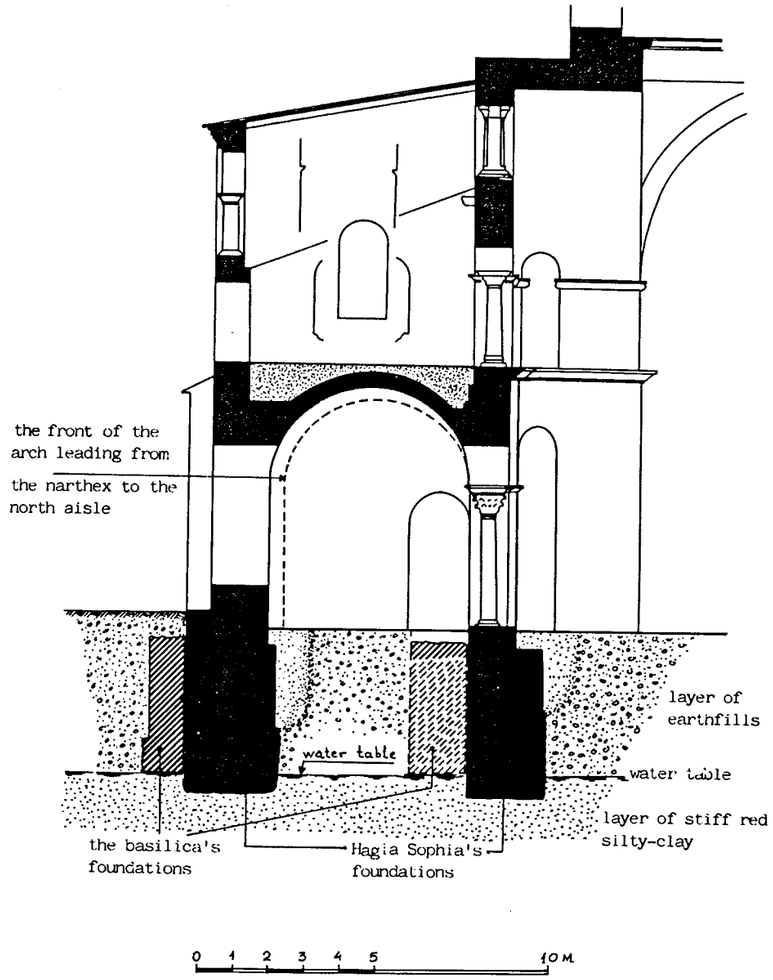
the front of the arch leading from the narthex to the north aisle
layer of earthfills
water table
water table
layer of stiff red silty-clay
the basilica's foundations
Hagia Sophia's foundations
0 1 2 3 4 5 10M

Fig. 53. Hagia Sophia; cross section with foundation footings, north aisle.

steps formed on their free side (Figure 53). The upper step, 30 to 40 cm below the present floor, served as a leveling guide for the original floor, while the lower one, 1.8 to 2.5 m below the first step, marked the bottom trench into which rubble mixed with mortar had been poured as the first phase of construction. Above this step, the foundation wall has a proper facing, indicating that it was built in the normal way.

The basic idea behind the foundation system was to create a single unit of continuous footings, up to 2.6 m wide, under the perimetrical walls, and a second unit, 2.3 to 4 m wide, under the system of piers and columns at the central nucleus (Figure 52). A conscious endeavor to link the two units is evident at two points: (a) on the east side of the cruciform center, which is directly linked to the tripartite chancel; and (b) at the west end of the same unit, where a 2.6-m-wide foundation acts as a link with the outer lateral walls,

Fig. 54. Hagia Sophia, prothesis: relieving arch over the basilica's foundation.

albeit indirectly, owing to the intervening foundation of the earlier basilica. Since no part of the central area of the narthex has been excavated, it is impossible to say whether there was ever another link between the foundation of the central nucleus and that of the west wall of the church, parallel to the foundation of the basilica; it seems probable, however. The foundations of the four heavy, square piers supporting the dome appear as simple projections from the central unit and reach the same depth as the rest of it. It is interesting that the two east piers have a wider foundation than those on the west, a feature that does not appear to serve any particular purpose.

As had already been mentioned, the early Byzantine church of Hagia Sophia occupied the western section of the huge, ruined basilica that had formerly occupied the site, and the Byzantine architect was obliged to design the new building within the limitations imposed by the remnants of the old one. Apart from architectural problems, then, he also had to cope with serious structural and statical problems. An examination of the plan of the foundations reveals that the architect carefully avoided seating any part of the new building directly on top of the old foundations, by designing openings or relieving arches wherever the two were forced to meet (Figure 52). The first solution was used at the west wall of the narthex and the east walls of the aisles, while the second occurs at the lower zone of the apses of the parabemata (Figure 54).[5]

The principle of making the foundations independent was adhered to so

5 A similar solution was used for the early Christian apse, which was added to the east end of Thessaloniki's Roman Rotunda. A semiarch was built at the point where the apse's wall met the Roman structure, in order to avoid seating part of the wall on the Roman foundation.

strictly that it not only dictated the bounds of the original system of architectural proportions, but also imposed some rather odd and unaesthetic solutions, as in the case of the wide arches between the narthex and the lateral aisles. In a quite unorthodox manner, when viewed from the aisles, the fronts of these arches are seen to vary in width from 0 to 35 cm (Figure 53), simply because the architect did not want to build a pilaster against the walls of the central nucleus, as he had done against the outer walls, owing to the presence of the foundation of the basilica at these points. The fact that the architect did all in his power to avoid founding even minor parts of the new building on the remains of the old shows that he was well informed about the behavior of foundations, and particularly the problems resulting from different degrees of settlement and their effects on the masonry of the superstructure.

The Superstructure

The Structural System

Bearing in mind the loads and thrust flow through the solid masonry toward the ground, we can identify two structural systems in Hagia Sophia: a basic system carrying the principal loads of the cruciform nucleus and the dome, and a secondary one that supports only itself and that depends to a certain extent on the basic system. The secondary system is to be found at the lateral aisles and the narthex, which, together with the galleries, run round three sides of the cruciform center.

The principal elements of the basic system are (a) the large dome with its short, heavy drum; (b) the four barrel vaults supporting the dome; and (c) the four "composite" piers at the corners between the arms of the cross. These piers, which are pierced in two directions in such a way that small corner bays are formed within their mass at ground and gallery level, carry the barrel vaults forming the arms of the cross as well as parts of the vaults belonging to the secondary system.

The secondary system comprises all the structural elements, vaults, walls, and colonnades, of the lateral aisles, the narthex, and the galleries. Although the ground-level arcades at the north and south arms of the cross belong to the secondary system, the fact that they increase the stiffness of the basic structural system should not be ignored. However, the corresponding gallery-level arcades under the north, south, and west barrel vaults, which originally sustained the low timber roof of the second phase, are purely secondary elements today. In the original design of the church, the secondary structural system was planned to include the vaults over the galleries and the sustaining transversal arches. These arches, which acted as a link between the basic and the secondary structural system at gallery level, corresponded to the buttresses evident today against the north and south facades at ground level. The buttresses may thus be considered an essential element of the secondary structural system.

The tripartite sanctuary may be considered an independent system, which plays an important part in restraining any outward movement of the eastern composite piers.

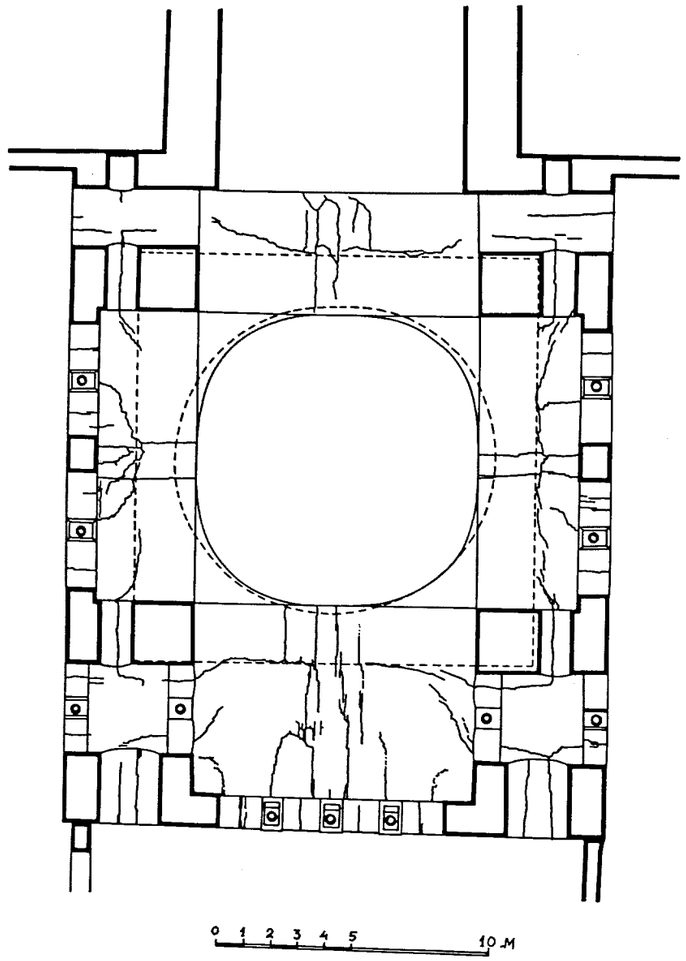

Fig. 55. Hagia Sophia; plan of the central nucleus with the existing cracks (dashed lines indicate the dome and its square base).

The Principal Structural Elements

The Dome. The church's present dome dates from the second construction phase, whereas the baseline, marked by the marble cornice, belongs to the first. We have no idea of the form of the original dome. Nevertheless, judging from the known examples from the preceding period, it is highly likely that it was designed without a drum, or at least with a very low one. All one can safely deduce from the surviving original baseline is the diameter of the first dome, which was some 10.20 m. It is worth noting that the original baseline is not perfectly circular, but rather squarish in plan, a shape that resulted from the incompletely developed pendentives spanning the corners of the basic square (Figure 55). The whole arrangement reveals a distinctly timorous approach to the construction of these protruding sections, which were themselves very large and would have projected strongly over the space below.

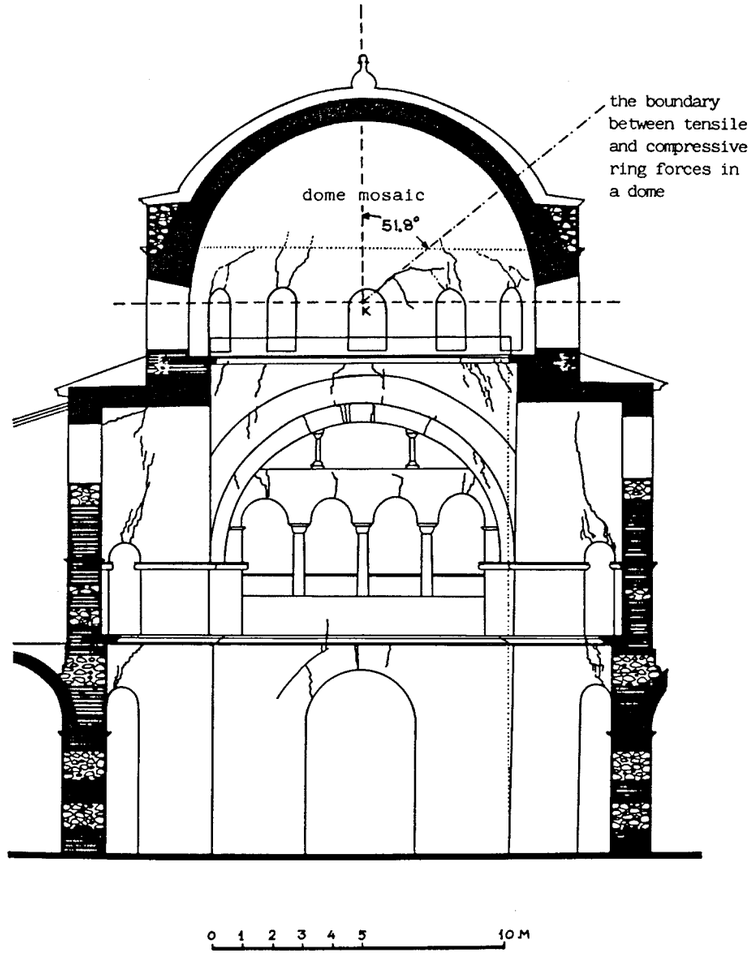

Fig. 56. Hagia Sophia; cross section of the central nucleus, looking west.

The existing dome has a larger diameter (11–11.65 m), thereby creating a narrow balcony at the base of the drum, as in the cases of Hagia Sophia and St. Irene in Constantinople. The load is thus shifted further toward the centers of the barrel vaults that support the dome, and this is even more obvious at the north and south vaults owing to the dome's particular plan. In fact, the hemispherical dome, which rests on a low drum some 2.10 m high, is not quite circular in plan: Its north–south diameter is 65 cm greater than its east–west diameter, which means a difference of 3 Byzantine feet, which cannot, of course, be accidental.

From a structural point of view, we have detailed knowledge of the dome of Hagia Sophia. The hemispherical shell and the externally square drum belong to the same construction period. The drum is pierced by twelve windows, which extend very little beyond the level of the hemisphere's springing in the interior, while on the exterior the cubic structure reaches a height 3.4 m above the marble cornice marking the baseline.

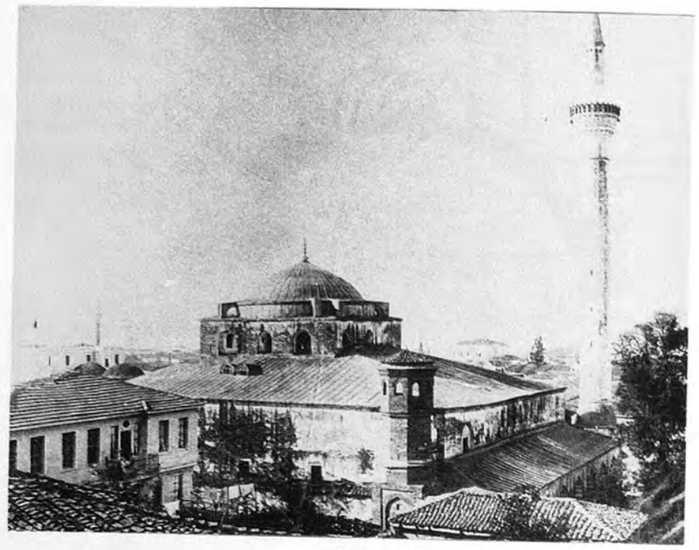

Fig. 57. Hagia Sophia from the northwest before the fire in 1890.

The square base consists of alternating courses of brick and rubble masonry, while the hemispherical shell is exclusively of brick. The shell is approximately 70 cm thick, which means that two rows of brick were used; but there is a reinforced band 1.50 m high and some 1.10 m thick at the base, above the square drum, which consists of three rows of bricks. This band is further reinforced externally by a second, cylindrical drum, which is contemporary with the rest of the dome and built of rubble masonry with hydraulic mortar.[6] Thus, in the lower part of the dome, where the tensile ring forces are greatest, the critical cross section of the shell is at least 1.70 m thick on the east–west axis and 1.50 m thick on the north–south axis. The reinforced band comprises a section of a curve corresponding to an angle of 33 degrees (Figure 56).

The cylindrical upper drum was further reinforced during the Turkish period. Four pairs of small flying buttresses, now completely destroyed, were added at the corners on top of the square base of the drum (Figure 57). In the drum, in the band containing the windows, there are no timber tie beams, in contrast to other domes of earlier and later date. As for the marble cornice at the base of the drum, wherever its constituent marble pieces are visible along the narrow balcony there are no iron cramps between the blocks. Since other examples of this practice are known, it may be supposed that such features exist in the sections of marble blocks lying under the masonry of the square base of the dome.[7]

The Barrel Vaults. The barrel vaults are built exclusively of brick with a reinforced section at either end. One of these sections, 2.10 m wide, is directly below the square base of the dome and is 1.05 m thick, consisting of three rows of bricks. The sections of the barrel vaults near the springings are constructed in such a way as to ensure a uniform cross section, while a section around the crown comprising about a third of the vault's span is built in the form of two superimposed arches, the upper arch having the thickness of a single brick. The rest of the vault is 70 cm thick (i.e., two rows of bricks), and there is a second reinforced band, in the form of a rib, at the external fronts. This rib is 1.20 m wide and 1.20 m thick and has the appearance of an arch over the diaphragms of the arms of the cross at gallery level (Figure 56).

6 Theocharidou, *Architecture*, 45, figs. 14b and 15.

7 Concerning the use of iron cramps in the marble cornices of Hagia Sophia, Constantinople, see R. Mainstone, *Hagia Sophia; Architecture, Structure and Liturgy of Justinian's Great Church* (London, 1988), 70–1 and fig. 93.

The Composite Piers. The composite piers consist of four (the west) or three (the east) supports of different shapes separated by a small space. The strongest support takes the form of a square pier with sides measuring 2.30 m. Like the walls, the massive vertical elements are constructed with the familiar courses of hewn stone and rows of bricks, whereas the features that link the vertical elements – arches and barrel vaults – are built exclusively of brick (Figure 56). These composite piers comprise two distinct sections, one at ground level and the other at gallery level; the two sections are built to precisely the same plan, but are significantly different in height. At ground level they are three times as high as the upper sections: 7.55 and 2.55 m, respectively. It must be said that the linking of the two sections at gallery level with arches, barrel vaults, and groin vaults considerably increases the strength of the piers, which essentially bear the major load of the whole structure.

Construction Materials

Stone, brick, and mortar are the main materials used in the original structure. In the first construction period very little timber was used, only for tie bars over the capitals of the columns, whereas in the later period it was given a more substantial role in the roofing of the galleries.

The original masonry forms successive horizontal bands of bricks and ashlar stones bound with a powerful crushed-brick mortar. The brick bands extend through the whole thickness of the walls, but the ashlar stones probably form only the two outer faces, with a rubble core with plenty of mortar in between. The ashlar stones are mostly a mixture of limestone and sandstone, the latter characterized by a high content of shells, making it a material that is soft and easy to quarry and hew, though not of high quality. Their average compressive strength, as determined in the laboratory, is ca. 50 MPa.[8] The stones vary in size, but measure on average 0.25×0.40 m; larger ones, up to $0.5–0.6 \times 0.9–1.0$ m, are found in the lower bands. This type of stone is not available locally, but was probably brought from the west coast of the Kassandra Peninsula at least 30 km away.[9]

The bricks are of the usual Thessalonian size, whole bricks measuring $40 \times 30–32 \times 4–4.5$ cm and half bricks $40 \times 15–18$ cm. They are of very good

8 The tests relating to the mechanical properties of the stones and bricks were carried out in the laboratories of the Polytechnic School of Thessaloniki University and the Thessaloniki Department of the Ministry of Public Works.

9 Concerning the historical circumstances and the problems involved in transporting stones from the Kassandra Peninsula, see Theocharidou, *Architecture*, 127, 156–7.

quality, solid, and with a high proportion of aggregate mixed in with the clay. A mineralogical examination has shown them to be made from local clay, and a differential thermal analysis test applied to a limited number of specimens revealed that they were kilned at just under 700°C.[10] The average compressive strength of the few specimens tested in the laboratory was 13.2 MPa.

Even more important, structurally speaking, are the mortar and the mortar bed joints, and they consequently deserve a more detailed discussion. The joints are as thick as, or slightly thicker than, a single brick, and as a rule, the building mortar itself also forms the outer skin of the joint. Its more fine-grained appearance on the surface is due to greater pressure being applied to the fresh joint by the trowel, rather than to the use of fine-grained mortar on top. The mortar is a strong, pink, crushed-brick lime mortar, which could quite correctly be considered a fine concrete, owing to the great amount of coarse aggregate it contains. Sieve analysis of a limited number of specimens has shown that the gradation of the aggregate in the mortars used for the first and second construction periods, which are identical in composition, falls within the limits recommended by our modern code of practice (DIN 1045/1972) (Figures 58 and 59).[11]

Crushed brick is a vital component of this mortar, both in the form of brick powder and as a coarser inert material. In fact, apart from a certain proportion of sand, the filler used in the mortar is almost exclusively broken brick, with the occasional incidence of fine gravel, which was evidently contained in the sand. A differential thermal analysis test applied to some coarse grains from the mortar specimens has shown that they were obtained from bricks kilned at the same temperature (ca. 700°C) as those used in the construction. This low firing temperature ensured that the presence of fine brick powder gave the mortar exceptional hydraulic properties, though this does not seem to be the only hydraulic factor in the mortar.[12] As for the coarse, porous aggregate, it helped the mortar to set more quickly, gave better adherence between binder and filler, and at the same time made the concrete lighter than if gravel had been used instead. These combined qualities make for a quicker building process, especially when vaults have to be constructed without centering. Recent laboratory research by M. Karaveziroglou, I. Papayianni, and G. Penelis, of the Polytechnic School of Thessaloniki University, has revealed a further beneficial property of crushed brick in lime mortar: Its addition to the mortar helps to reduce creep and shrinkage during setting, which is vital to avoid deformation in very thick joints.[13] For the same reason, the use of a concrete-like mortar seems to be a crucial factor, especially when the progressive building process imposes considerable loads on the incompletely hardened mortar joints in the lower part of the structure.

10 The mineralogical and thermal analysis of the bricks was carried out by the chemists M. Kessissoglou and E. Mirtsou in the chemical laboratory of the Archaeological Museum of Thessaloniki.

11 The granulometric gradation of the old mortar was analyzed by the author in the laboratories of Heslington University, York, England.

12 The hydraulic qualities of Hagia Sophia's mortar are being investigated by I. Papayianni at the Polytechnic School of Thessaloniki University.

13 G. Penelis, I. Papayianni, and M. Karaveziroglou, "Pozzolanic Mortars for Repair of Masonry Structures," in *Structural Repair and Maintenance of Historical Buildings*, ed. C. A. Brebbia (Southampton, 1989), 161–9; M. Karaveziroglou, I, Papayianni, and G. Penelis, "Time-dependent Deformations of Brick Masonry," in *Structural Conservation of Stone Masonry*, 247–55 (Athens, 1989, preprints).

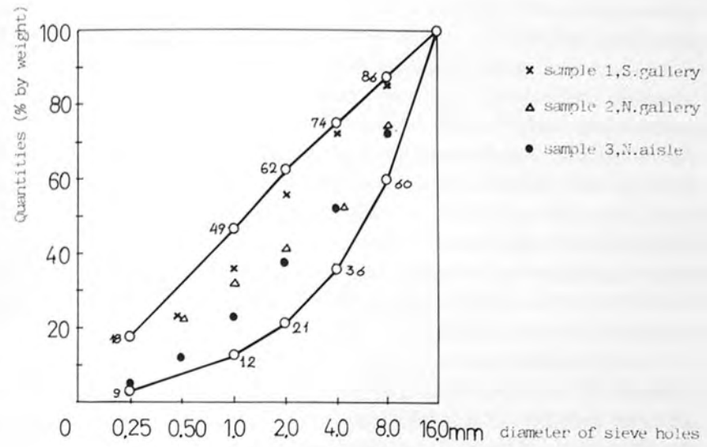

Fig. 58. Hagia Sophia; granulometric gradation of the aggregrates in the original construction mortar.

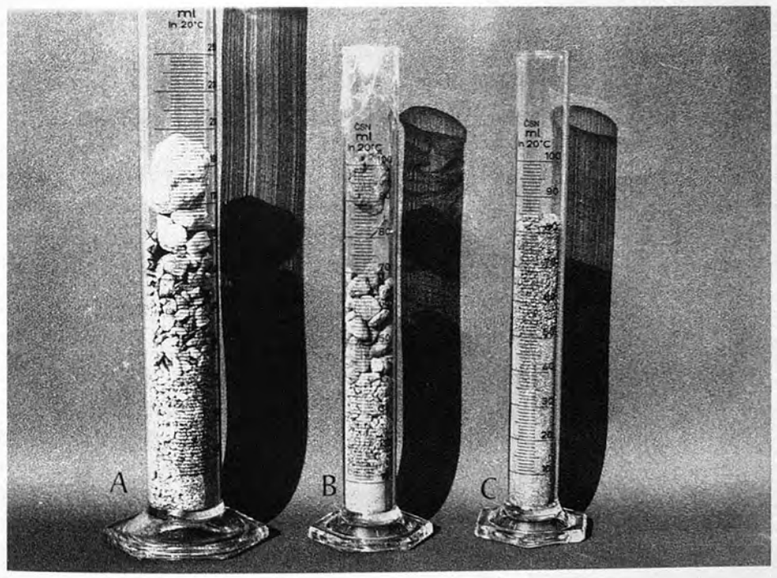

Fig. 59. Hagia Sophia; aggregrates of building mortars: (A) early Christian basilica; (B) Hagia Sophia's first construction phase; (C) Hagia Sophia's fourth construction phase.

As far as the mechanical properties of the mortar are concerned, the situation is far from clear. The values obtained by laboratory tests, from specimens taken from a limited number of cores, cannot be considered absolutely reliable, owing to defects in the specimens or to unreliable testing conditions and evaluation of the individual specimens.[14] A reliable test of one specimen has given a compressive strength of 5 MPa and a modulus of elasticity equal to 4,000 MPa, whereas an unreliable series of tests involving twenty speci-

14 The tests relating to the mechanical properties of the old mortar were carried out in the laboratories of the Polytechnic School of Thessaloniki University and the Thessaloniki Department of the Ministry of Public Works.

mens produced compressive strength values ranging from 1.1 to 10MPa, with an average of 3 MPa.

I believe that more credible values have been obtained through a nondestructive method (i.e., hammer testing), though the results have not been calibrated directly.[15] Since laboratory testing of Hagia Sophia's mortar presented the above-mentioned problems, the relevant results obtained for the Rotunda were used as a basis for calibrating the measurements in Hagia Sophia. It should be noted that hammer testing was conducted on both buildings using the same methodology and instruments. In the case of Hagia Sophia, it produced an average compressive strength value for the mortar of 4.62 MPa, which is very close to the value obtained by the only completely reliable laboratory examination.

Superficial ultrasonic testing was used to determine the mortar's modulus of elasticity, which was found to be ca. 2,000 MPa (as opposed to 4,000 MPa given by the only reliable laboratory examination).[16] It is worth mentioning that the mortar of Hagia Sophia has been the strongest tested so far from the Byzantine monuments at Thessaloniki. The relevant values obtained from the mortar of the Rotunda are 44.7 MPa for the Christian and 19.37 MPa for the Roman part, and the mortar of Acheiropoitos gives 12.30 MPa.

Structural Defects: Seismic Behavior

My observations focus on the cruciform nucleus, because this is not only the building's most complicated structural system, but also its most original one. The secondary structural system, involving the lateral aisles and the basic structure of the galleries, consists of a patchwork from different periods and cannot therefore serve our purpose.

Distorted Walls

The vertical elements – walls, colonnades, and composite piers – of the cruciform nucleus are plumb, with one exception: The top of the square northwest pier inclines 9 cm (i.e., 1.2%) northward, measured at the top of the pier under the marble cornice marking the gallery floor. This slight inclination continues as far as the vertical front of the north barrel vault, so that the diameter of the original baseline of the dome is elongated northward for about 19 cm (Figure 56). It is impossible to say when this problem first arose, since the joints between the marble blocks forming the cornice at the baseline have been repointed repeatedly and any iron cramps between them are not visible. Nevertheless, if one takes for granted certain factors (such as the accuracy of the original construction), it seems that, in contrast to the other three piers, the face of the northwest pier is flat from the ground floor to the gallery. The ground-floor sections of the other piers project some 7 to 8 cm beyond the

15 The hammer testing was carried out by the civil engineers A. Saklabanis and T. Magoulas of the Ninth Ephorate of Byzantine Antiquities.

16 Concerning the effectiveness of the ultrasonic tests, see G. Penelis, M. Karaveziroglou, K. Stylianidis, and D. Leontaridis, "Repair and Strengthening of the Rotunda, Thessaloniki," *Restoration*, 20–30.

faces of the gallery sections. If this is not accidental (and it would appear that it is not), it seems that the builders endeavored to correct the defect in the course of construction, when they started working on the galleries.

The fact that this problem is an isolated case indicates a localized phenomenon, probably settlement of the foundation of this particular pier, rather than distortion due to accumulated loads on a structure with thick and still insufficiently hardened mortar joints. This is further proof of the excellent properties of the hydraulic mortar the Byzantine builders used in Hagia Sophia, as explained in the preceding section. If, as seems likely, an initial settlement occurred beneath the northwest pier during actual construction, the pier certainly continued sinking at later periods, too. There is clear evidence of this at the marble cornice marking the level of the gallery floor. The section of the cornice at the top of the pier is 5 mm lower than the section to the north of the crack at the arch linking the pier with the north wall. Furthermore, the section of cornice at the top of the pier is not absolutely horizontal, but sinks slightly toward the middle of the nave.

Cracks

Most of the cracks visible today are old ones that were reopened by the 1978 earthquake. Some of those in the barrel vaults were visible in the painted plaster before the earthquake, and in several cases old iron nails have been found hammered into the old cracks and covered with successive layers of plaster. It is not possible to say exactly when or in what order the basic cracks were formed.

The Dome

Despite its considerable size, the dome of Hagia Sophia presents very few and insignificant cracks, in comparison with the domes of the rest of Thessaloniki's Byzantine churches. Of course, most of the interior of the hemispherical shell is covered by the mosaic, but the cracks, usually 1 to 5 mm wide, which start from the tops of the window arches, have virtually disappeared by the time they reach the mosaic. Only three of the cracks visible in the interior of the dome also continue through to the outside of the cylindrical drum, and these, as an on-the-spot investigation has shown, proceed no further than the reinforced zone at the base of the shell (Figure 56).

From these observations alone, one can deduce that the statical behavior of the dome as a shell is most satisfactory. But since the dome has not yet been the subject of a detailed statical analysis, it is not possible to answer the question that most interests us: precisely how effective the Byzantine design was from a statical point of view.

The Four Barrel Vaults

The cracks in the four barrel vaults are the most severe in the whole structure, and those in the crowns were the only ones visible before the 1978 earth-

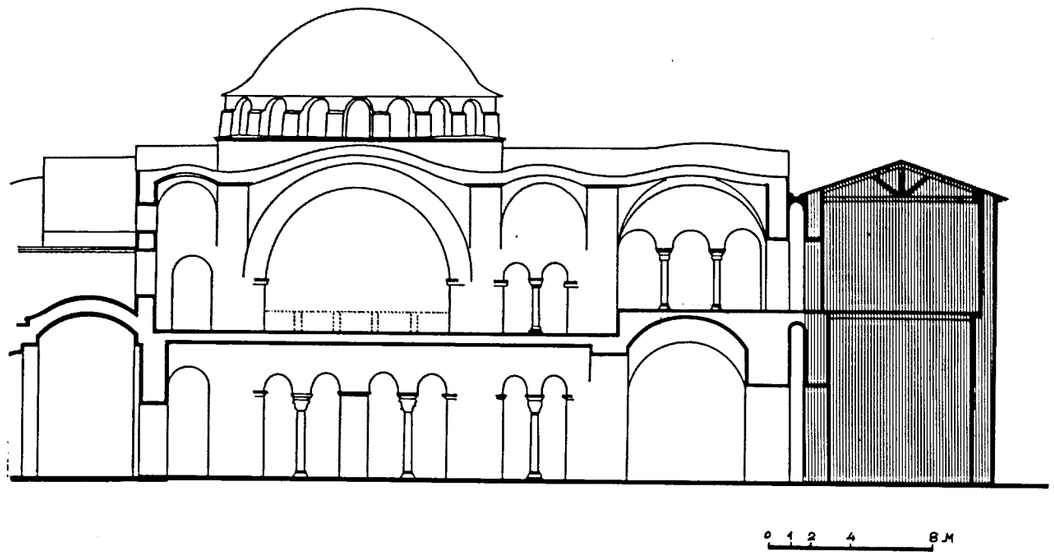

Fig. 60. Hagia Sophia; reconstruction of its original form with the earlier exonarthex: longitudinal section through the north gallery.

quake. The cracks follow the same characteristic pattern in all four barrel vaults. Basically each barrel vault comprises two sections: The inner one (which is larger in cross section), under the square base of the dome, is cracked around the crown along its axis, whereas the outer section is separated from the inner one by a number of cracks parallel to the front of the vault just where the cross section changes. In this outer section, the cracking follows a pattern typical of dome-bearing barrel vaults in Byzantine cross-in-square churches: The cracks form a characteristic triangle, with its apex at the center of the free side of the vault and its base on the opposite, rigid side (Figure 55).

The two sections appear, therefore, to have separate statical functions: The one with the larger cross section, under the dome, acts as an arch, and the rest as a barrel vault with three rigid sides. If, moreover, we look carefully at the system of cracks formed in the vaults of the corner bays (within the system of the composite piers), we see that the square corner piers tend to break away from the unity of the composite piers. In other words, the system of the dome, together with the reinforced sections of the barrel vaults and the square piers, tends to act independently, especially in the event of an earthquake.

It is difficult to venture any categorical remarks on the question of how the Byzantines understood the complicated seismic behavior of a structure. In this connection, some enlightening information may be gained from the case of the exonarthex of the earlier basilica and the way it was connected to the west end of the new church (Figure 60). From a statical point of view, the two buildings were diametrically opposed in terms of their structural conception. The old, two-story, timber-roofed exonarthex was a light, tall, narrow structure, which was quite vulnerable to seismic action in an east–west direction,[17] whereas the new, vaulted church was a heavy, rigid structure, equally

17 Concerning the problems involved in the reconstruction of the church's original form and the exonarthex of the ancient basilica, see Theocharidou, *Architecture*, 53–68 and figs. 20–3.

resistant to lateral forces in any direction. Any movement of the compact new structure, then, particularly in an east–west direction, could have proved fatal to the old attached one. The way the two structures were linked together indicates that the Byzantine architect took these negative effects seriously into consideration.

In between the two structures, whose foundations alone were in direct contact, there was a 70-cm-wide gap, which was covered, probably by a narrow barrel vault at the level of the gallery floor, and possibly at roof level, too. At two points only, vertical hinges were provided where the basilica's nave pilasters were inserted into special openings left in the west wall of the new church. There can be only one explanation for this unorthodox solution: The wide joint between the two different parts of the church enabled the structures to move in different ways with minor damage limited to the connecting elements. If we bear in mind that similar solutions were not provided in other, comparable cases – such as the Justinianic narthex of St. Irene in Constantinople, which was incorporated into the remodeled vaulted church after 740 – the example of Hagia Sophia in Thessaloniki takes on considerable significance, since it can be seen as a further step in the Byzantine understanding of the complicated seismic behavior of buildings.

STRUCTURAL STUDIES OF HAGIA SOPHIA AND RELATED BUILDINGS

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FINITE-ELEMENT MODELING OF THE FIRST AND SECOND DOMES OF HAGIA SOPHIA

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KENICHIRO HIDAKA, AND H. NAKAMURA

The horizontal thrusts at the base of a dome can be easily balanced by a tension ring that is sufficiently strong. It would have been quite natural for Fossati to apply this kind of structural understanding when, in the mid-nineteenth century, he was given the opportunity to restore the dome of Hagia Sophia. The reinforcement of the dome with a set of iron rings would have been rational. Justinian's architects, however, had been confronted with a far more complicated problem: to support the dome as a uniaxial structure of rotated arc by another structure related to the longitudinal disposition of the church. Thus, what we see is characterized by the interplay of enormous forces and reactions acting through a miraculous fusion of domical centrality and longitudinal axiality.

In this sense, the restoration work of Fossati, apart from its structural efficiency (or inefficiency), had nothing to do with the structural properties of the dome and the supporting structure as a balanced unity. If we now attempt to make a precise structural assessment, it is because we hope to avoid depriving the monument of the subtle structural stability inherent in it.

This essay presents a method of analyzing the dome of Hagia Sophia by applying the finite-element method (FEM). This effective method of analysis, however, does not clarify everything automatically. The analyst's intuitive understanding of the relevant structure plays an essential role in the process of approximation and hence in the process of modeling. We hope that the present work offers one of the starting points of discussion toward a better understanding of the great monuments of the world.

It would perhaps not be of interest here to review the history of structural interpretation concerning Hagia Sophia from Choisy to the present.[1] Main-

The authors express their gratitude to the Ministry of Education and Culture of Japan for financial support and also their great appreciation to Dr. K. Iida, professor emeritus of Nagoya University, Dr. K. Mashita, professor of Tokai University, and Dr. T. Hara, associate professor of Tokuyama National College of Technology for their guidance and discussions.

1 A. Choisy, *L'art de bâtir chez les Byzantines* (Paris, 1883).

stone confirmed the general structural assessment of the fabric in the 1960s.[2] He explained unequivocally how the weight of the central dome was taken or counterbalanced by the supporting structures – in particular, how the northern and southern arches lean outward and how the eastern and western transversal arches deflect inward. The elastic deformation patterns of the spherical dome and the semidome were the basis of his analysis. His interpretation regarding the flow of forces has been shown graphically in his well-known figure.[3] In addition, he examined the probable cause of the collapse of the eastern and western semidomes. However, any discussion concerning the dynamic behavior of the structure and the viscoelastic analysis of creep effect lies beyond the scope of the present essay. Nonetheless, the structural analysis of Hagia Sophia, be it static or dynamic, is inevitably founded on the contribution of Mainstone.

The contribution of Thode[4] is also important in that it was the first attempt to analyze Hagia Sophia on the basis of structural theory. Thode applied the classical theory of membrane stress analysis. We intend to compare his results with ours from the viewpoint of analytical methodology. Our considerations and conclusion with respect to this problem will be published elsewhere.

Assumption and Approximation in the Process of Modeling

In our previous work we compared the profiles of the first and second domes, applying two-dimensional FEM analysis with elastoplastic joint elements.[5] Admittedly, to make a two-dimensional model implies the supposition of an axis-symmetric structure. The dome we imagined in this analysis was supported on a uniform circular base, though the sectional area (and therefore the stiffness of the base) of the first dome was assumed to be greater than that of the second.

We used this type of two-dimensional model to infer the structural significance of axis-symmetric elements of the dome – for example, the arched window openings in the lowest part. As mentioned by Mainstone years ago[6] and also by Mark in his latest book,[7] the dome has already been cut through practically in the same direction and in the same area where meridional cracking would develop owing to the tensile forces in the hoop direction. According to our analysis, the tensile area in the second dome does not extend over the window. This result agrees with the opinions of Mainstone and Mark.

The dome rests on the arches and pendentives. The supporting structure as a whole is not axis-symmetric: Massive double arches are applied on the north and the south sides, and semidomes fringed by single arches are used

2 R. J. Mainstone, "The Structure of the Church of St Sophia, Istanbul," *Transactions of the Newcomen Society* 38 (1965–6), 23–49.
3 R. J. Mainstone, *Hagia Sophia: Architecture, Structure and Liturgy of Justian's Church* (London, 1988).
4 D. Thode, "Untersuchungen zur Lastabtragung in spatantiken Kuppelbauten" (Dissertation, Darmstadt, 1975).
5 K. Hidaka, T. Aoki, and S. Kato, "Structural Stability and Profile in the Dome of Hagia Sophia, Istanbul," in *Proceedings of the STREMA International Symposium*, Florence, 1989) (Southhampton, 1989), 267–76.
6 See note 2. 7 R. Mark, *Light, Wind and Structure* (Cambridge, Mass., 1990).

on the east and the west sides. Three-dimensional models are required to understand how the thrust of the dome is received by the lower structure.

As a preliminary step, we analyzed the dome alone, applying three-dimensional models composed of nine-node heterosis shell elements. The analytical models correspond to one-quarter of the actual structure with the following boundary conditions: Rotation is fixed at the base and at the apex; horizontal movement is allowed at the base but not at the apex; and vertical movement is allowed at the apex but not at the base.

We have prepared two types of analytical model: A and B (Figure 61). These are treated differently in the lowest part, where the dome is ringed by the buttress-like piers. Model A comprises double rows of shell elements in this part, the inner row corresponding to the domical shell and the outer row corresponding to the projection of the buttress-like piers. In Model B, the entire thick wall of the lowest part is represented by a single row of elements with transitional trapezoidal elements above them. The alternation of the low buttress walls and the window openings is ignored, partially because it was considered in the previous two-dimensional analysis and partially because we are seeking a comprehensive understanding of the structure from the dome down to the principal pier on the ground level. In Model B, however, it is possible, when necessary, to distribute elements in such a way that the structural effect of the window openings is taken into consideration. Consequently, the mesh of Model B is smaller than that of Model A. Total numbers of elements and nodes in these two models are given in Table 2 (see p. 111).

The shell element consists of eight layers, the yielding condition of which is given in Figure 62. Figure 63 shows the stress–strain relationship of concrete characterizing the element. For the sake of expediency, nonlinear strain hardening has been ignored, though a small amount of tension stiffening is assumed. In order to assess the effectiveness of a circumferential tie against the outward thrust, elements corresponding to the base of the dome are composed of nine layers: eight normal layers of concrete with an additional layer representing a smeared iron ring. Values for the total cross-sectional area of the smeared iron ring were chosen to be 0.50, 500, and 5,000 cm^2. Material constants used in the analysis are listed in Table 1.

As one might expect, the results of the analysis agree well with those of the two-dimensional elastoplastic analysis. Figures 64 and 65 show that the horizontal outward displacement of the lowest edge, in Models A and B, is far larger in the first dome than in the second. In the lowest part of Model A, the outward displacement is larger on the inside than on the outside. This pattern of displacement may be caused by the composition of the model itself, where the weight and thrust of the dome are received more directly by the inner elements of the base. It seems unnecessary to make such a complicated model by doubling the elements corresponding to the lowest part of the dome. Consequently, Model B is preferable.

Membrane forces per unit length in the meridional and hoop directions of the dome (Model B) are shown in Figure 66. In the case of the first dome, the hoop tension appears above the window zone and reaches a substantial level at the base. In the second dome, by contrast, the hoop tension develops at the elevation of the window openings. The distribution of meridional bending moment in the dome (Model B) is shown in Figure 67.

The outward bulgings of both the first and second domes are very small.

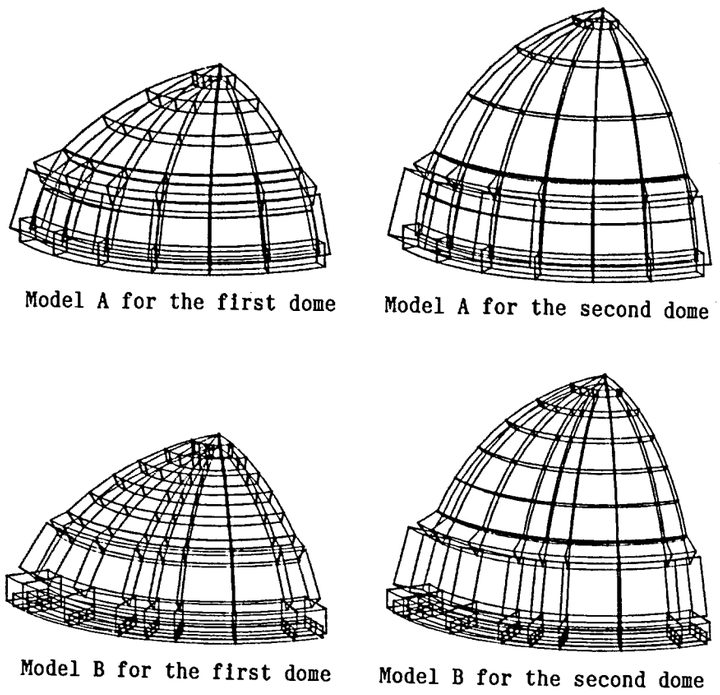
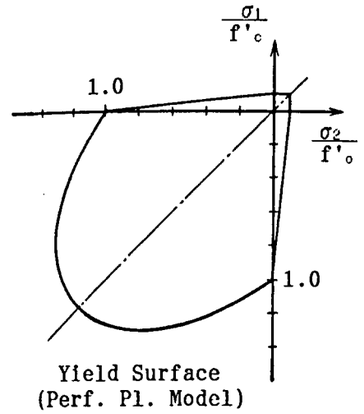


Fig. 61. Numerical Models A and B for the first and second domes (nine-node heterosis shell element).

The structure may be stiffer because rotation is not allowed at the points of support. The supporting condition is dependent on the stiffness of the supporting structure, K_s. As already stated, we assumed that $K_s=0$ (the dome supported on rollers) in general cases. But analyses using other values of K_s have also been carried out. The varying stiffness of the supporting structure is indexed by the stiffness of iron, that is, the stiffness of the tie ring that,



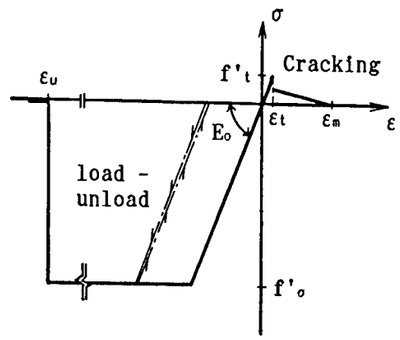


Fig. 62 (left). Yielding condition applied in the analysis for the concrete constitutive model.

Fig. 63. Stress–strain relationship for the concrete constitutive model.

Table 1. *Material Constants Used in the Finite Element Analysis*

Concrete	
Young's modulus = 1.0×10^5kg/cm²	
Poisson's ratio = 1/6	
Weight per unit volume:	
dome = 1.7t/m³	
lower structure = 1.7t/m³	
Ultimate strength (kg/cm²):	
tensile = 2	
compressive = 200	
Ultimate strain:	
compressive = 0.003	
Tension-stiffening parameter:	
$\epsilon_m = 0.002$	
$\alpha = 0.5$	
Iron chains	
Young's modulus = 2.1×10^6kg/cm²	
Elasto-plastic Young's modulus	$=2.1\times10^4$kg/cm²
Weight per unit volume	=7.85t/m³
Yield stress	=1600kg/cm²

according to documents, was embedded by Fossati on the level of the dome cornice. The result of a series of analyses is given in Figure 68. The difference between Model A and Model B is negligible. Nor does the variation of the stiffness K_s appear to affect any part of the structure substantially, except for the dome. The profile of the dome seems to be the most important factor affecting the stability of the structure.

Elastic Analysis of the Dome and the Supporting Structure

In view of the significance of the principal supporting structure in the overall structural system of Hagia Sophia, our analysis should be advanced a step further toward a series of elastoplastic analyses of the primary structural system in its totality. However, we are still in a tentative stage of the elastic analysis. Though the models now considered are essentially the same as those applied in the preceding analysis, they are clearly more complicated (Figure 69). Two models corresponding to one-quarter of the structure, C and D, have been proposed. Model C comprises the main pier, the buttress pier, the secondary pier, the semidome with the barrel vault at its outermost point,

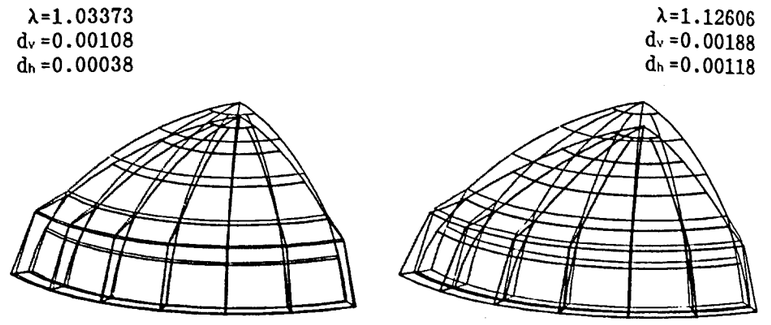


Fig. 64. Deformation of the dome (Model A). The stiffness of the supporting structure $K_s=0$. λ, Load parameter (λ = 1.0 corresponds to the structure under self-weight); d_v, vertical displacement at the apex; d_h, horizontal displacement at the base.

the transversal arch, the doubled arch framing the tympanum, the pendentive, and the dome (Figure 70). Model D is more inclusive, comprising the outer wall of the aisle, the gallery roof, the tympanum, the exedra, the wall separating the nave from the narthex, and the square dome base covering the pendentive on the back side (Figure 71). The dome of Model C is Model A and the dome of Model D is Model B.

Thus, the secondary as well as the primary structural components are brought together in Model D. Indeed, the structure is very complicated (as in the arcaded exedra connecting the main pier and the secondary pier) or, worse, obscure (as in the inner construction of the space concealed by the dome base and the pendentive). However, it still may be of some value to compare the analytical results obtained from simplified models with considerations based on intuitive structural understanding. Total numbers of elements and nodes of Models C and D are given in Table 3.

The results of the analysis are shown graphically in Figures 72 through 75 and in Table 4. In every case, the circle delineated by the base of the dome

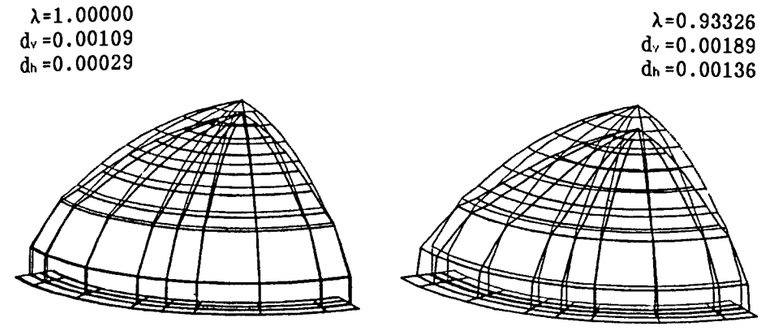


Fig. 65. Deformation of the dome (Model B). The stiffness of the supporting structure $K_s=0$. λ, Load parameter; d_v, vertical displacement at the apex; d_h, horizontal displacement at the base.

deforms into an ellipse. The massive double arches on the north and south sides deflect outward due to the thrust of the dome. On the eastern and western sides, however, the upper part of the great semidomes exerts inward thrust to such an extent that the summit of the adjacent transverse arch displaces not outside but inside in spite of the outward thrust of the dome. This oval displacement pattern of the base of the dome, though the result of the elastic analysis, is in accordance with the actual state of the structure. At the outermost point of the semidome, the thrust pushes down the edge of the adjacent barrel vault, which again qualitatively agrees with what was recorded by Van Nice.[8]

Admittedly, the main piers and buttresses are deformed owing to the thrust exerted by the upper structure. According to our results, the direction of the deformation deviates slightly southward (or northward) from the diagonal of

8 R. L. Van Nice, *Saint Sophia in Istanbul: An Architectural Survey*, Dumbarton Oaks Studies, 2 (Washington, D.C., 1980), plate 43.

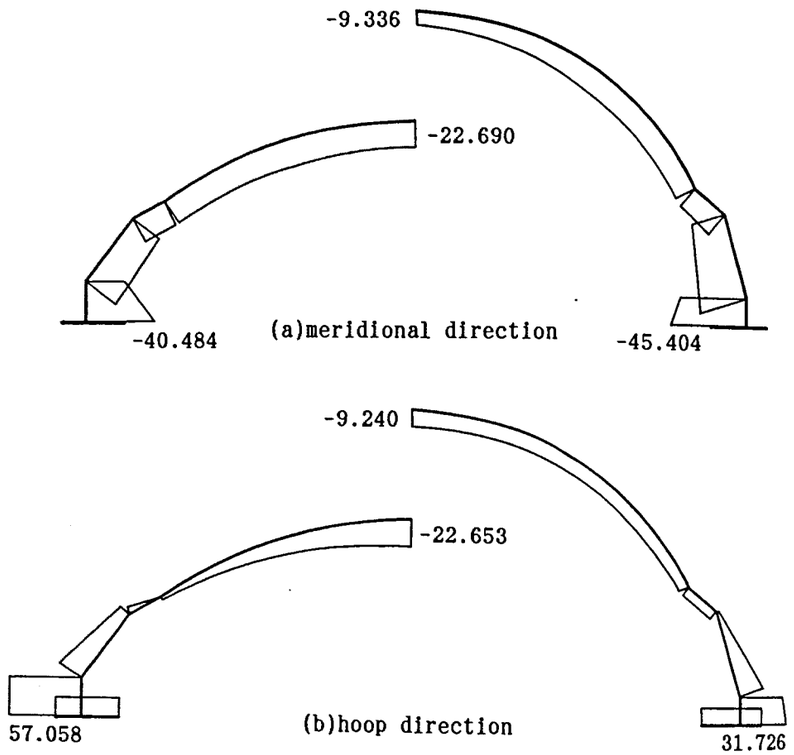
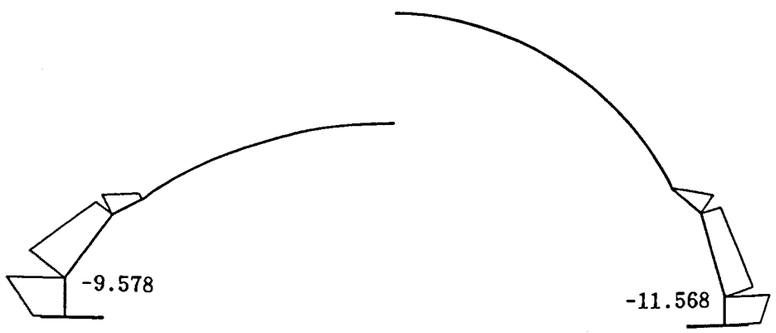
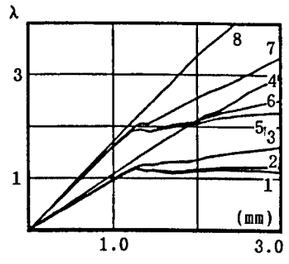


Fig. 66. Membrane forces per unit length in the meridional and hoop directions (Model B under self-weight; t/m).

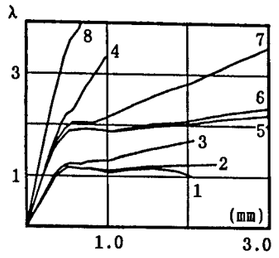
Fig. 67. The distribution of meridional bending moment (Model B under self-weight; t/m).



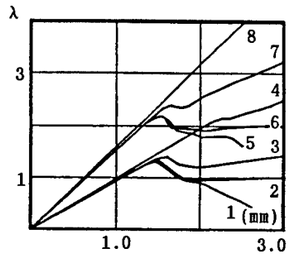
the central square defined by the four piers. This tendency makes us suppose that the magnitude of the component of the thrust transmitted through the western (or eastern) transverse arch and the adjacent area of the pendentive is greater than the other component due primarily to the double arches. In this respect, Mark has provided specific data. The east–west reaction at the top of the main pier is reported to be 540,000 kg and the north–south reaction to be



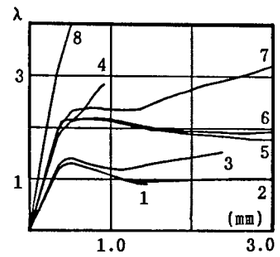
(a)vertical displacement at the apex of the dome in Model A



(b)horizontal displacement at the base of the dome in Model A



(c)vertical displacement at the apex of the dome in Model B



(d)horizontal displacement at the base of the dome in Model B

Fig. 68. Relationship between load parameter λ and displacement. K_{s1}, stiffness of the supporting structure of the first dome; K_{s2}, stiffness of the supporting structure of the second dome. 1, $K_{s1}=0$; 2, $K_{s1}=1$; 3, $K_{s1}=10$; 4, $K_{s1}=100$; 5, $K_{s2}=0$; 6, $K_{s2}=1$; 7, $K_{s2}=10$; 8, $K_{s2}=100$.

Table 2. *Total Number of Nodes and Elements in Models A and B*

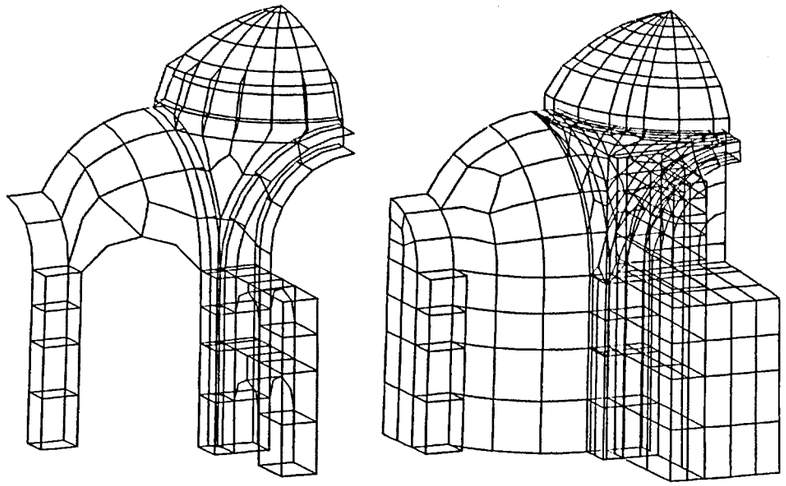
	A	B
Nodes	268	469
Elements	51	92

Table 3. *Total Number of Nodes and Elements in Models C and D*

	C	D
Nodes	1244	2406
Elements	220	479

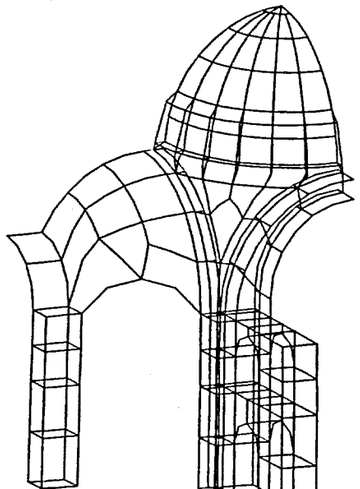
400,000 kg. The qualitative results of our analysis do not oppose these values.

Displacements of and around the pier are smaller in Model D than in Model C. The rigidity of the structure and the weight of the semicubic dome base over the pendentive surely contribute to a lessening of the relative displacement in Model D. In Model C, the displacement of the first dome is not noticeably different from that of the second dome. This holds for Model D. In contrast to Models A and B, the supporting structure seems to be stiff enough to absorb, so to speak, the formal disadvantage of the first dome. A more detailed study of the structural behavior both in the elastic and in the plastic regions would clarify some of the difference between the two profiles.

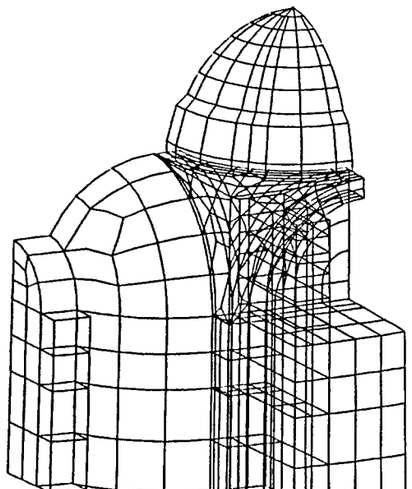


(a)First dome, Model C

(b)First dome, Model D



(c)Second dome, Model C



(d)Second dome, Model D

Fig. 69. Numerical analysis models of the dome and the supporting structure (nine-node heterosis shell element).

Table 4. *The Values of Displacements (mm)*

Position	Direction		First dome Model C	First dome Model D	Second dome Model C	Second dome Model D
Dome apex						
Apex	Vertical	w	−8.19	−5.76	−8.32	−5.56
Dome base						
West	Horizontal	u	−2.71	−1.50	−2.90	−1.62
	Vertical	w	−10.54	−6.44	−10.14	−6.28
South	Horizontal	u	−0.95	−0.72	−1.57	−0.87
west		v	1.00	0.19	0.85	0.16
	Vertical	w	−7.52	−4.83	−8.00	−5.03
Double arch top						
Upper	Horizontal	v	1.83	0.85	2.65	0.96
south	Vertical	w	−6.00	−3.73	−6.29	−4.00
Lower	Horizontal	v	2.65	1.07	3.31	1.19
south	Vertical	w	−5.63	−3.49	−6.01	−3.69
N-S arch base						
West	Horizontal	u	1.86	0.65	1.94	0.66
		v	2.01	0.91	2.04	0.93
	Vertical	w	−1.33	−1.25	−1.37	−1.28
Inter	Horizontal	u	1.88	0.60	1.95	0.62
sect.		v	1.87	0.75	1.91	0.77
	Vertical	w	−0.96	−1.26	−1.00	−1.29
Double arch base						
Upper	Horizontal	u	1.77	0.53	1.56	0.55
south		v	1.88	0.75	1.78	0.77
	Vertical	w	−1.29	−1.31	−1.55	−1.33
Lower	Horizontal	u	1.73	0.47	1.80	0.49
south		v	1.36	0.61	1.41	0.62
	Vertical	w	−0.95	−1.44	−0.99	−1.47

Concluding Remarks

Countless questions have been and will be asked concerning the structure of Hagia Sophia. For example, is the dome spreading further and accumulating deformations owing to the deflection it has suffered up to the present? Were the partial collapses of the dome in the tenth and fourteenth centuries caused by vertical, horizontal, or combined earthquake motions? Questions such as these can be studied in light of the long history of the monument. If we understand the oval deformation of the circular base of the dome, the following questions arise: Are the rigidity and/or strength in the east–west direction sufficient, and are they greater than in the north–south direction? Are the rigidity and/or strength in the north–south direction satisfactory in view of

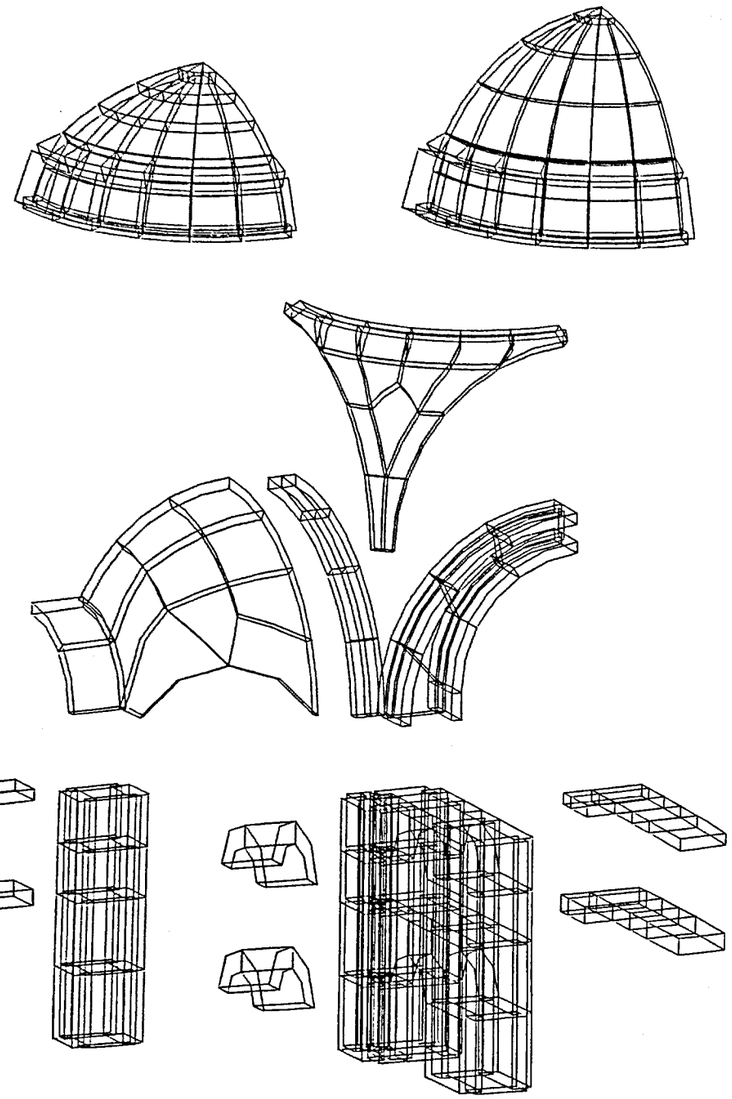


Fig. 70. Decomposed representation of Model C.

the stability of the overall structure? One of the most fundamental tasks may be to determine how the dome is supported. The structural relationships between the dome and the supporting structures have been clarified by Mainstone, and we initiated our study of Hagia Sophia by confirming his interpretation through structural analysis. Though the actual deformation is too large

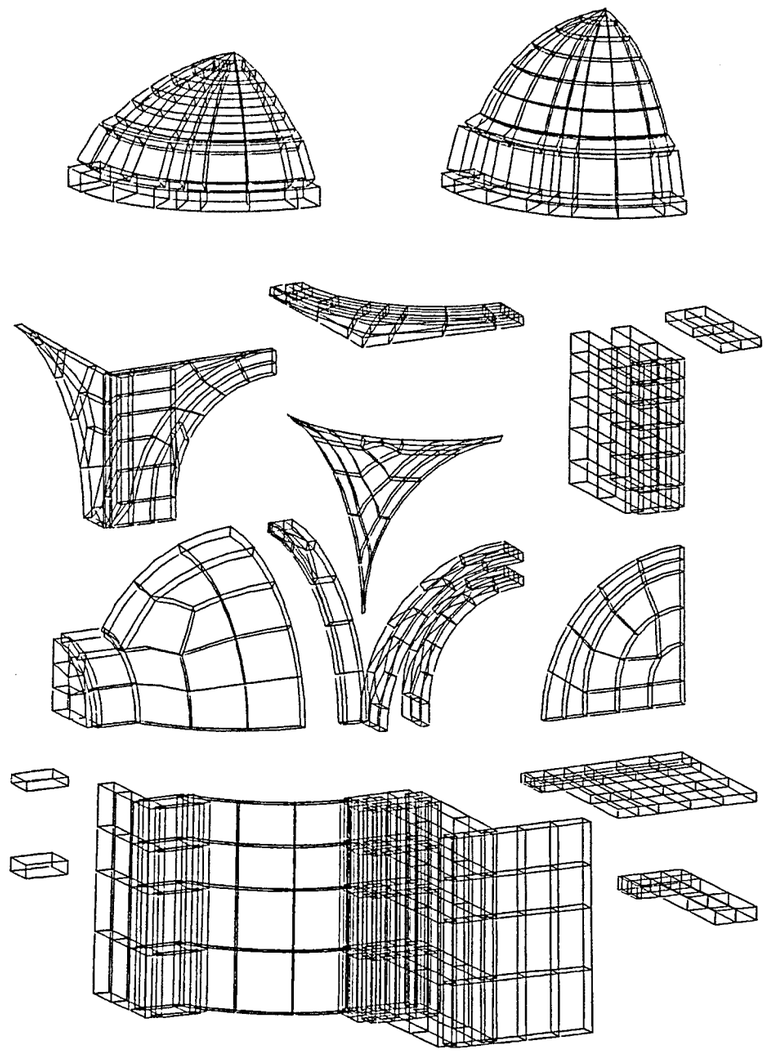
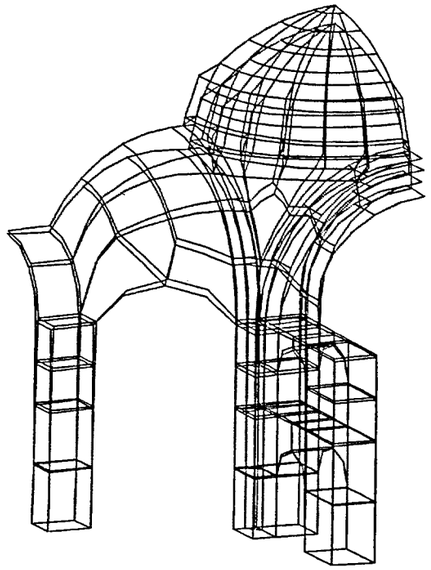
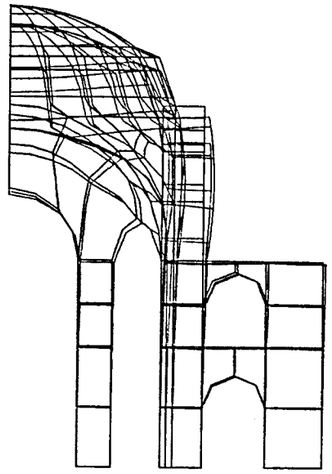


Fig. 71. Decomposed representation of Model D.

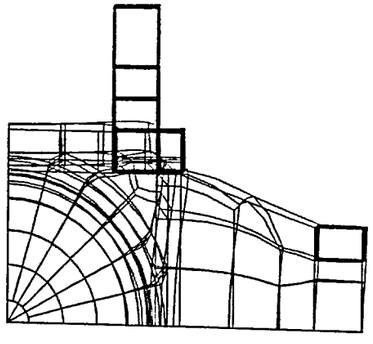
to be analyzed in the elastic or elastoplastic phase of the material, our results correspond well to the oval deformation observed along the base of the dome. The agreement leads us to suppose that our modeling methods will also be effective in more complicated analyses concerning historical masonry structures.



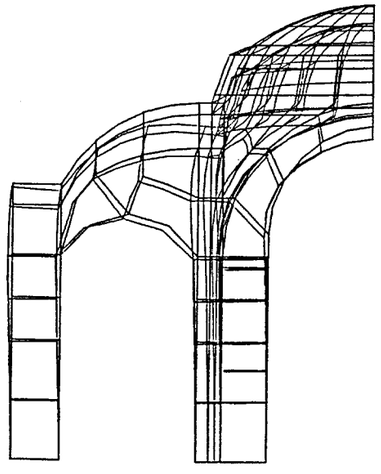
(a)perspective



(c)yz-plane

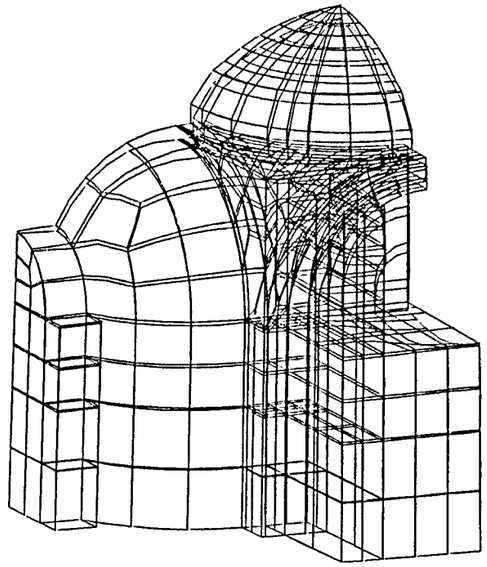


(b)xy-plane

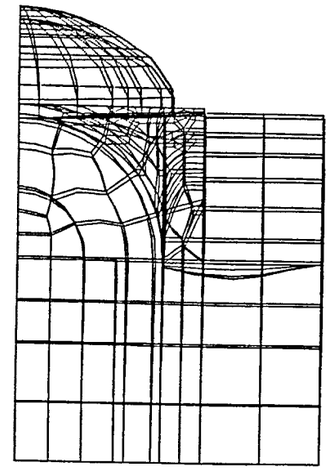


(d)xz-plane

Fig. 72. Elastic deformation of the structure under self-weight (first dome, Model A).



(a)perspective



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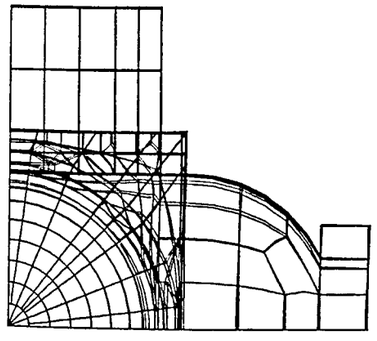

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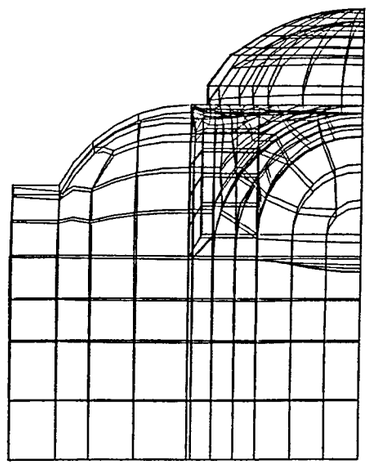
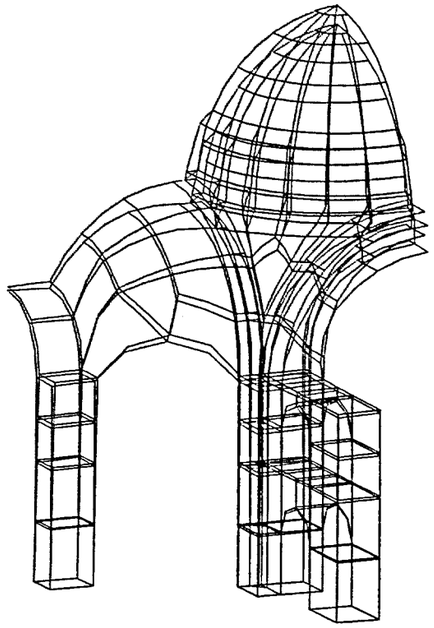
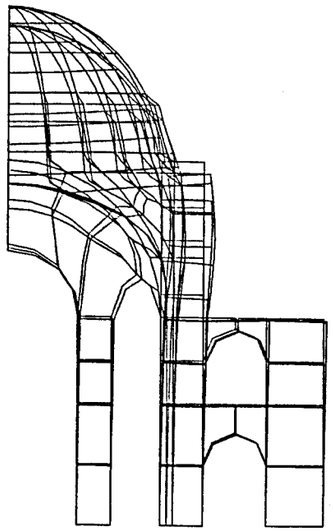


(d)xz-plane

Fig. 73. Elastic deformation of the structure under self-weight (first dome, Model B).



(a)perspective



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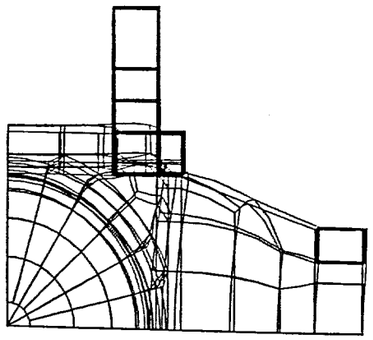
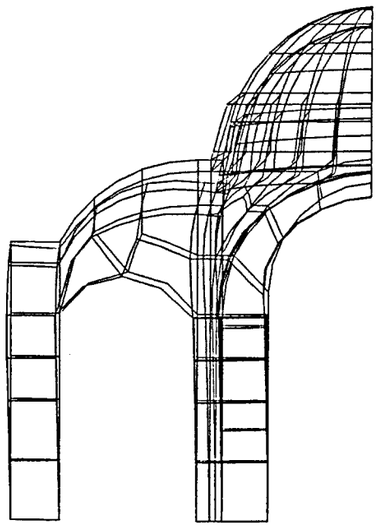
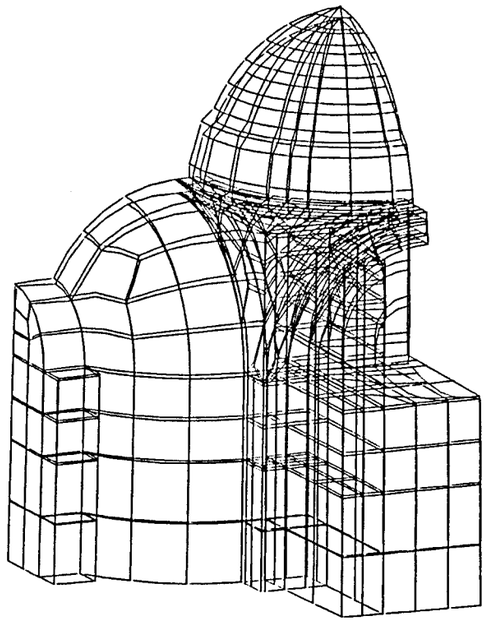


(b)xy-plane

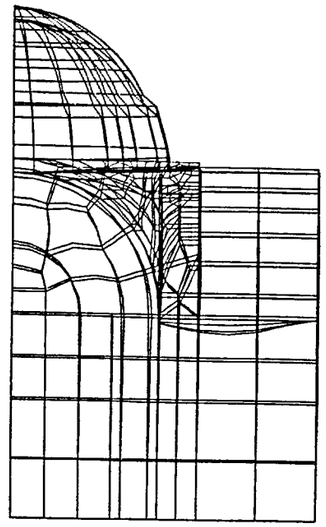


(d)xz-plane

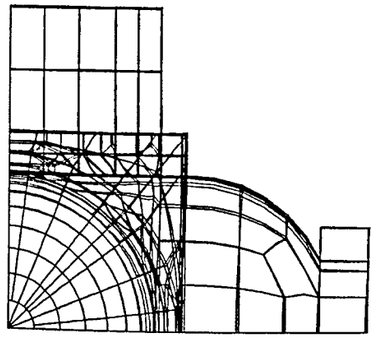
Fig. 74. Elastic deformation of the structure under self-weight (second dome, Model A).



(a)perspective



(c)yz-plane



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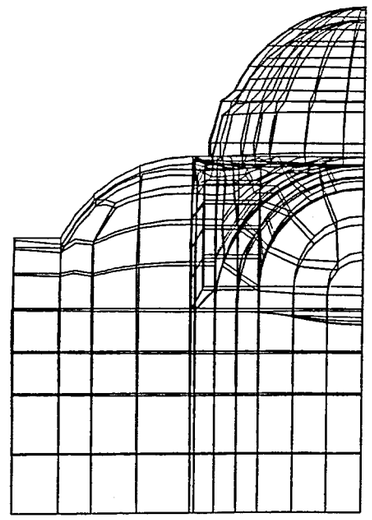


(d)xz-plane

Fig. 75. Elastic deformation of the structure under self-weight (second dome, Model B).

PRELIMINARY REPORT ON AN INTEGRATED STUDY OF THE STRUCTURE OF HAGIA SOPHIA: PAST, PRESENT, AND FUTURE

ROBERT MARK, AHMET Ş. ÇAKMAK, AND MUSTAFA ERDIK

The application of the techniques of modern structural analysis to the study of historic monuments has contributed significantly, particularly over the past decade, both to architectural-historical methodology and to the art of building restoration. This study of the Hagia Sophia, certainly one of the most important and also one of the most complex historic building structures, carries the approach into uncharted realms. By using more sophisticated numerical modeling than that employed in previous building studies, we will attempt to account for the sequence of both initial and later construction as well as the response to longtime environmental loadings. We anticipate that, when used together with data gathered from on-site tests, the model will also be able to predict the building's response to a major earthquake.

The study consists of three major tasks. The first is to organize available data on the building's structural form, sequence of construction, and subsequent physical history over almost fifteen centuries.[1] These data include observations of longtime structural deformation under the action of gravity, fractures, and distortions emanating from short-duration earthquake forces, as well as structural interventions from the numerous campaigns of restoration. Fortunately, a great deal of this information is already available from published sources, including the comprehensive survey of the building completed by Robert Van Nice and the text of Rowland Mainstone that summarizes much of the known information on the building's fabric and endeavors to reconstruct its long-term structural behavior from observations of dislocations.[2]

The numerical modeling at Princeton University was carried out by Colby Swan, graduate research assistant in the Department of Civil Engineering and Operations Research. Katherine Hill, an undergraduate in the Program in Architecture/Engineering, assisted in this research.

1 A concise survey of the Byzantine literary evidence on the Hagia Sophia with particular emphasis on Procopius and the *Diegesis* is given by C. Mango, "Byzantine Writers on the Fabric of Hagia Sophia," in this volume; and Ottoman sources are discussed by G. Necipoğlu, "The Life of an Imperial Monument," also in this volume.

2 R. L. Van Nice, *Saint Sophia in Istanbul: An Architectural Survey* (Washington, D.C., vol. 1, 1965; vol. 2, 1980); R. J. Mainstone, *Hagia Sophia: Architecture, Structure and Liturgy of Justinian's Great Church* (London, 1988). See also O. Gürkin, S. Çamlıdere, and M. Erdik, "Three-Dimensional Digital Coordinate Data and Best-Fitting Spheres of the Main Dome of Hagia Sophia," in this volume.

The second task of the study is the creation of a numerical model that will account for both short- and long-term, nonlinear material behavior, including the consequences of cracking and effects of component deformation during the initial sequence of construction and from subsequent structural modifications. Model input will reproduce steady-state, gravity- and dynamic earthquake-generated loadings.

The third task of the study concerns the monitoring and interpretation of accelerometer measurements from the actual building structure under the action of dynamic forces, which include ambient vibrations produced by wind and nearby traffic and possibly a seismic event. Some of the initial efforts within these separate categories of the study are described in the following sections.

Structural History

The construction of the Hagia Sophia, begun early in 532, proceeded in more or less horizontal layers until the erection of the main arches intended to support the great dome. (The sequence of building construction, with the exception of the side-aisle and gallery vaults, is illustrated in Figures 76a–f). From sixth-century accounts it is known that, even before the completion of the main arches, the builders were disquieted by exceedingly large deformations of the main piers.[3] Mainstone has suggested the probable use of flying centering, unsupported from the floor below, for the assembly of these arches.[4] In this event, it is unlikely that the centering could have been adequately tied to prevent horizontal reactive forces from impinging directly on the piers; and it is these forces that must have produced the large, initial deformations.

In response to the evident distress, the builders reinforced the arches connecting the main and buttress piers and filled some of the passages within the piers. According to Mainstone, the exterior buttresses to the north and south were also extended upward to their present form (as illustrated in Figure 76e, concurrent with the construction of the main semidomes). Assuming that the limestone–ashlar main piers are fixed into the bedrock at their bases, their form makes them appreciably stronger along the east–west than along the north–south axes. And although Emerson and Van Nice have suggested that weakness of the footings might have allowed the piers to rotate,[5] the preliminary model of the structure, discussed later, indicated relatively low maximum bearing pressures compared with the bearing capacity of the solid bedrock below these footings. We inferred also that the massive surcharges were placed above the pendentives (Figure 76f) before construction of the dome

3 Procopius, *On Justinian's Buildings*, trans. H. B. Dewing, *Buildings* (London, 1940), sec. 7.

4 *Hagia Sophia*, 204. On the basis of the assumption that the building was constructed as closely as possible to established datum planes – in particular, that upright faces were truly vertical when built – and that additions made to previously deformed surfaces were also installed true, Mainstone estimates that the piers inclined 20 to 25% of their present-day inclination when the arches were completed, and that by the time the first dome was installed, it was 40 to 45% of today's pier inclination (ibid., 205).

5 W. Emerson and R. L. Van Nice, "Hagia Sophia, Istanbul: Preliminary Report of a Recent Examination of the Structure," *American Journal of Archaeology* 47 (1943) 412.

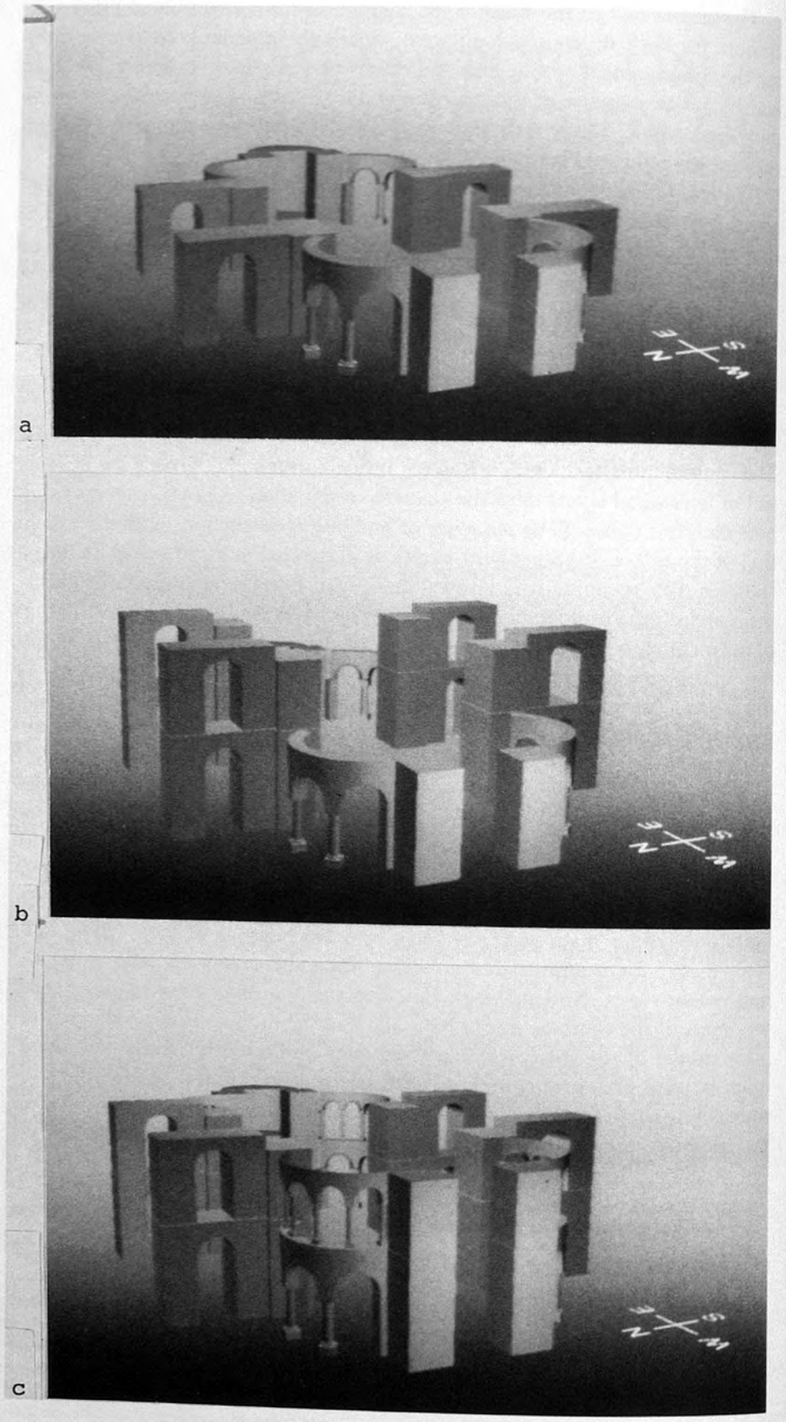


Fig. 76. Hagia Sophia construction sequence: (a) ca. late 533; (b) ca. late 534; (c) ca. early 535; (d) ca. mid-535; (e) ca. late 535; (f) ca. mid-536. (Computer graphics by D. Erten)

began. Incredibly, the entire structure seems to have been standing by the time of dedication, in December 537.

In 558, the great central dome fell after being subjected to two major earthquakes: one in August 553 and the second in December 557. A second dome having a higher profile than its predecessor was then erected in 558–62. Despite partial collapses after an earthquake in the tenth century and again after another in the fourteenth, the general form of the second dome remains unchanged today. But structural repairs associated with these incidents as well as other adversities have involved the placement of much additional buttressing around the entire structure.

Structural deformations are large enough to be easily measured and in many instances are discernable to the naked eye. Hence, it is possible to verify the validity of the model by comparing the predicted deformations with those of the actual structure. The most significant evidence of the greatest forces at work in the structure are the inclinations of the four main piers, which tilt outward (along the directions of both axes). This deformation is undoubtedly caused by a combination of outward thrusts from the great dome and from the four main arches that connect the piers and support the base of the dome. The inclination of the piers is greater in their lower sections, indicating that the upper sections were erected plumb after an initial deformation had occurred below. Their present inclination is greater in the north–south than in the east–west direction by a factor of about 2 below gallery level and about 3 at the gallery level and above.[6]

The vertical, dead load of the superstructure causes the arch haunches to bow outward, pushing the supporting piers out of plumb along the axis of the arches. The adjacent arches, supported on the same piers, are thus displaced laterally. Indeed, the crowns of the north and south arches exhibit such outward displacement. However, the east and west arches, despite a similar tendency to incline outward (but to a lesser degree, as already noted), exhibit net inward displacement. The transverse displacement of the east arch is greater than that of the west arch, which is consistent with the fact that the west arch was made thicker and wider during its reconstruction, whereas the east arch was rebuilt in the same manner as the original.

The aisle and gallery colonnades show the effects of the main pier deformations, even though they are essentially secondary structure. The outward inclination of many of the columns is startlingly evident; during the mid-1800s this inclination caused so much concern that several of the columns were actually severed from their bases and moved into a more upright position. Deformation is also evident in the lack of symmetry in the arches spanning the aisle and gallery walkways.

The exact functioning of the pendentives and even the solidity of their infill are unclear. The one major jog in the northeast pendentive is probably the result of difficulties in smoothing over an edge during reconstruction of part of the pendentive rather than a structural deformation. Deformation is evident in the four exedrae located at the corners of the church, and there are visible cracks at the bases of the exedra semidomes. Shear failures also run close to the main piers. These arches, like the others, show a depression of the crown as well as an inward deformation from the semidome. (However,

6 These data and much of the following are taken from Mainstone, *Hagia Sophia*, 87 and passim.

the deformation of the arch is not symmetric, since the exedra is bordered on one side by a main pier and on the other side by a secondary pier, both of which tilt in the same direction.) Radial cracking has occurred at the lower levels of the great dome as well as at the base of the semidomes. The dome base, originally intended to be 100 Byzantine feet on each side, is no longer square. This seems to have been the case even before the dome was installed, though the additional weight of the dome itself no doubt increased the pier displacements, changing the shape of the base even more.

Structural Modeling

Because of its complexity, the full structure of the Hagia Sophia has never been analyzed even under only dead weight.[7] A few attempts to model portions of the structure using finite-element modeling have been made,[8] but these were clearly described by their authors as only the first steps toward a complete structural study, one that would have the dual objectives of ascertaining precisely how the structure supports itself against gravity and of assessing its vulnerability to characteristic seismic excitation associated with tectonic activity along with North Anatolian fault.[9] Numerical analysis of the complete structure in all of its complex interpenetrating three-dimensional geometry would be a formidable task. Yet its behavior can be largely captured by considering the primary structural system of the building as shown in Figure 77.[10] The model to be generated will thus comprise the main, secondary, and buttress piers, upper and lower north and south arches (plus infill), main east and west arches (plus infill), pendentives (plus infill), main dome and two semidomes, east and west barrel vaults, exedra semidomes and arches, and the apse semidome.

The process for creating the numerical model begins with an elastostatic model of the complete primary structural system in which relatively little attention is given to constitutive models that describe the comprehensive behavior of the building materials, but much attention is devoted to geometric detail. The elastic material properties used for this model are the same as those used by other researchers in modeling ancient domed masonry structures.[11] From this preliminary model, features of the structure's behavior that are relatively insensitive to constitutive behaviors of the various key elements will be deduced – for example, thrust-to-weight ratios of the original and present-day domes, vector thrusts exerted on each of the piers, and regions of tension where cracking or other failure is likely.

7 Although estimates of "thrusts" and "distributions of principal stresses in the main superstructure" were first published by Mainstone in "Justinian's Church of St. Sophia, Istanbul: Recent Studies of Its Construction and First Partial Reconstruction," *Architectural History* 12 (1969), 41–3.

8 See R. Mark and A. Westagard, "The First Dome of the Hagia Sophia: Myth vs. Technology," in *Domes from Antiquity to the Present*, ed. I. Mungan (Istanbul, 1988), 163–72; and K. Hidaka, T. Aoki, and S. Kato, "Structural Stability and Profile in the Dome of Hagia Sophia, Istanbul," in *Structural Repair and Maintenance of Historic Buildings*, ed. C. A. Brebbia (Basel, 1989), 211–20.

9 Recent earthquake history can be obtained from Turkish sources, such as N. Pinar and E. Lahn, *Turkiye Depremleri Izahli Katalogu* (Istanbul, 1952).

10 Mainstone discusses a similar "primary" system in *Hagia Sophia*, 72–6.

11 See, e.g., S. Kato, K. Hidaka, and T. Aoki, "Analytical Studies of Historical Structure: The Florentine Dome of Santa Maria del Fiore," in *Shells, Membranes, and Space Frames*, ed. K. Heki (Amsterdam, 1986) 1: 225–33; and Hadaka, Aoki, and Kato, "Structural Stability," n 7.

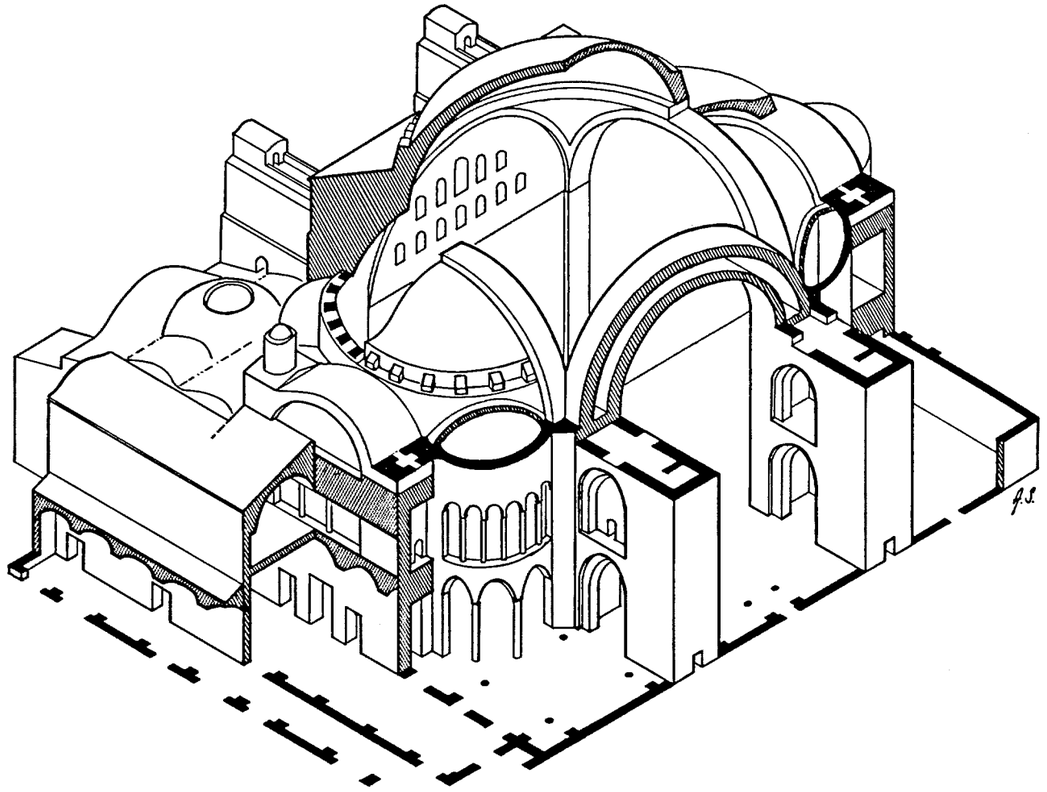


Fig. 77. Cutaway of Hagia Sophia illustrating major structural elements and infill behind pendentives. (Drawing by Amy Stein)

After we have assembled the preliminary model with accurate geometry, attention will be devoted to adding realistic material properties. Since it is highly unlikely that the actual structure can be core-sampled to obtain complete material property data, the properties of structural elements will be determined by inverse analysis. That is, constitutive features within the numerical model will be refined from those used in the elastostatic model so that the quasi-static displacements and deformations of the model agree with those observed in the actual structure. This portion of the work is expected to be computationally intensive, involving iterative calculations that will converge to realistic material properties. Rather than perform these iterative computations for the entire structure, we will isolate the constitutive behavior of elements in various parts of the primary structural system by taking the structure sequentially through its full history.

Numerical analysis of the structure to determine the behavior of the brick, mortar, and stone in various structural elements will comprise the bulk of this undertaking, since many nonlinear, irreversible mechanisms must exist to explain the large deformations observed. Among the potentially active mechanisms to be considered are fracturing of the domes and semidomes, plastic flow in mortar joints throughout the primary system, and frictional sliding between the massive stones of the main and secondary piers. Few, if any, of the parameters associated with the modeling of these phenomena in

Hagia Sophia are known a priori, and none can be truly determined from laboratory tests. Successful elucidation of the material properties is thus the key to assembling a realistic numerical model.

Upon completion of the inverse analysis that reproduces present-day and historically documented deformations in the structure, we will calibrate the numerical model further by making its dynamic response consistent with observations from ambient vibration tests performed on the actual structure. When the numerical model can reproduce both the existing historical deformations and observations from the full-scale dynamic experiments, this phase of the modeling will be considered complete.

After realizing the first objective of obtaining an understanding of how the Hagia Sophia structure "works," we will assess its vulnerability to future seismic activity by

(a) using available ground motion data from the vicinity of Istanbul to predict ground motions at the site of Hagia Sophia that are consistent with anticipated high-magnitude earthquakes along the North Anatolian fault;
(b) applying the ground motions obtained in (a) as excitation to the base of the numerical model of Hagia Sophia and analyzing the model's response to this earthquake loading; and
(c) if structural failure is indicated by the numerical model under seismic excitation, determining realistic modifications that might be applied to minimize the risk of failure.

The numerical model of Hagia Sophia will be based primarily on the finite-element code DYNAFLOW, developed at Princeton University. For both static and dynamic structural analysis, this code features three-dimensional continuum elements as well as curved-beam, shell and link elements – all having nonlinear and viscoelastoplastic capability – for modeling masonry behavior.[12] It is anticipated that virtually all of these will be used to model various features of the actual structure's behavior. In the event, however, that this library of elements does not prove adequate to reproduce measured behavior, new elements will be developed and added to DYNAFLOW. The element and material model libraries of this code are modularized and are therefore easily expanded without alteration to the main code.

Preliminary Results

The first phase of the study, elastostatic modeling under gravity loading, began with an investigation of the behavior of a series on increasingly complex forms, starting with the great dome on variable spring-boundary supports and gradually adding more of the primary structural elements, including the main arches, pendentives, semidomes with arches and short barrel vaults, appropriate surcharges, and the main piers, finally forming the coarse-mesh, quadrant model illustrated in Figures 78 through 80.[13]

12 J.-H. Prevost, *DYNAFLOW User's Manual*, Civil Engineering Department, Princeton University, 1988.

13 Even with the coarse mesh, the model contains 1,073 nodes with a total of 5,956 nodal degrees of freedom. Memory required for an in-core solution is 4.2 million 32-bit words. The physical constants are as follows; Young's modulus, 1.0×10^{10} Pa; Poisson's ratio, $\frac{1}{6}$; density, 1,700 kg/m^2.

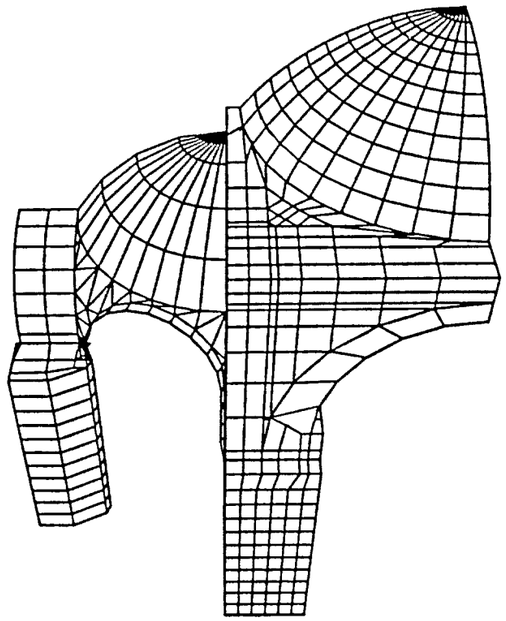
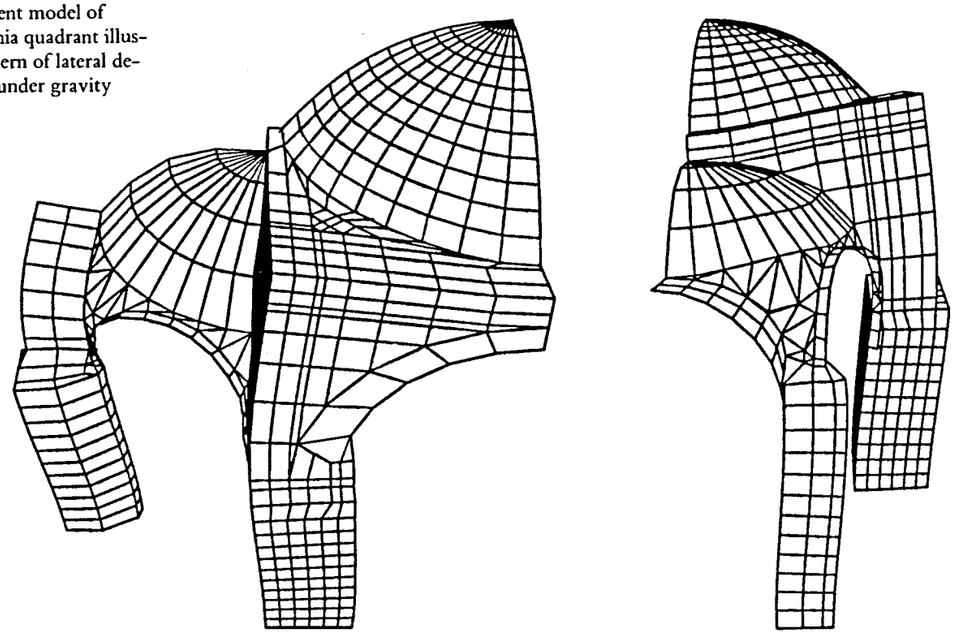


Fig. 78. Undeformed coarse-mesh, partial finite-element model of Hagia Sophia quadrant.

Fig. 79 (left). Coarse-mesh, partial finite-element model of Hagia Sophia quadrant illustrating pattern of longitudinal deformation under gravity loading.

Fig. 80. Coarse-mesh, partial finite-element model of Hagia Sophia quadrant illustrating pattern of lateral deformation under gravity loading.



The double main arches on the north and south were initially modeled as separate entities and then later connected by a structural infill so they act as a single unit. In the latter arrangement, the outward inclination of these arches is greatly reduced; indeed, with their double construction, the north and south arches are far stiffer than their counterparts to the east and west. The addition to the model of the solid-backed pendentives, which essentially form the base of the raised great dome, caused the crowns of all four arches to tilt inward – enough to overcome the outward inclination of the main piers – so that the absolute motion of the crowns was inward. The same tendency was observed even when the density of the added pendentive surcharge was reduced by three-quarters.

The main and secondary piers of the "full" model of the primary structure (but still lacking the visually dominant, yet problematic north and south buttresses)[14] exhibit outward inclination in both directions for approximately two-thirds of their height. Above that, the modeled piers incline inward, giving them a slight S-curve. For the main piers this inward inclination is enough to overcome the initial outward inclination, thus causing a net inward displacement at the crown of the arches. The displacement is larger for the east and west crowns, very likely owing to the greater east–west stiffness of the main piers (and hence the smaller outward displacements of their lower portions) and the interaction with the east and west semidomes. As would be expected, the crowns of the domes, semidomes, arches, and barrel vaults all settle downward, causing outward bowing of their haunches.

All of these results are but precursory at this stage of the analysis, since they do not reflect the ample evidence of irreversible creep and cracking that would lead to far greater deformations than predicted. There are also several places where adjacent structural members are not actually bonded together, but simply abut each other, which would further increase information and reduces the structure's capacity to resist shear forces. Discontinuities introduced during reconstructions employing different materials and building techniques further compromise the homogeneity of the structure, as well as alter its geometry. Nor does the simplified model take into account the fact that during the reconstruction of the west side, the arch, semidome, and part of the main dome were significantly stiffened while the parallel members on the east side were not. The eastern apse would also behave differently than the barrel vault in the corresponding location to the west. Yet in spite of all of these limitations, the model reveals some characteristic behavior of a structure of this geometry, the knowledge of which will influence future modeling as we begin to consider more realistic material behavior.

Dynamic Measurements

As a prelude to dynamic tests to be performed on the building structure, an elastic, finite-element model of the dome was designed at Bogazici University to determine its natural frequencies of vibration.[15] Four types of support

14 Mark and Westagard, "The First Dome," 170–1.

15 The SAP 80 model consisted of 160 shell elements of 0.78 m thickness. At the dome base was a ring made from 40 beam elements, 1.9 × 1.6 m in cross section. The ring, in turn, was supported

Table 5. *Dome Vibrational Modes*

	First natural mode, N–S oscillation	Second natural mode, E–W oscillation
Expected frequencies (model), Hz		
Fixed joints	8.98	10.56
Hinged joints	4.47	7.16
Springs (constant stiffness)	4.35	5.88
Springs (variable stiffness)	4.08	5.38
Observed frequencies, Hz	2.1	3.3

conditions were used: fixed joints, hinged joints, springs of constant stiffness, and springs of variable stiffness (stiffest over the pendentives, weakest in the north–south direction). The presently blocked pairs of windows to the north and south were also accounted for.

Six natural vibrational modes were found, with all but the sixth having the same form under all support conditions. The first vibrational mode corresponds to the lowest natural frequency of vibration, the second mode to the next lowest, and so on. And of course, the stiffer the structure is in a given direction of motion, the higher will be the frequencies of vibration for motion in that direction.

The first natural mode of vibration was a back-and-forth oscillation along the north–south axis (see Table 5). The second mode was the same sort of oscillation, but this time along the east–west axis. The third mode was a twisting back and forth around a vertical centerline. The higher modes were irregular, and so little energy is found in these higher frequencies that they would have minimal effect compared with that of the lower modes; hence, they will not be considered here.

To test this very approximate model against the actual frequencies of the dome, ambient vibrations were recorded using a four-channel recording system.[16] Four seismographs were used, each with a frequency of 0.5 Hz and a 70 percent damping coefficient, and the data were transferred to a computer with the aid of an analog-to-digital converter. The measurements were taken from the crown of the dome in the north–south, east–west, and vertical directions. The fourth measurement was taken at a reference point located at the base of the dome, over one of the pendentives.

It was expected that the building would exhibit greatest motion in the north–south direction on the basis of results from the preliminary model and the expected first mode of vibration; this was confirmed by the ambient measurements. The first significant peak in the power spectrum appears at 2.1 Hz, and its amplitude is significantly higher in the north–south direction than in any other direction, confirming the north–south direction mode of oscillation. The next significant peak is at 3.3 Hz, and its amplitude is greatest in the east–west direction and small in all others; so the second mode of oscillation must be in the east–west direction, confirming expectations. The frequencies of higher modes, however, cannot be conclusively determined from this initial set of observations. Information for the first two vibration modes is summarized in Table 5.

The results confirm the nature of the first two modes of vibration, but there is a discrepancy between the predicted and observed dominant frequencies – no doubt owing mainly to cracks in the actual dome. A more realistic, nonlinear model that accounts for the cracking will give far better agreement. But even so, the information developed up to this point is important for our study because the measured frequency spectrum falls within the frequency content of typical earthquakes observed on the North Anatolian fault.

by 40 nearly vertical columns of 2.0×1.2 m cross section (3.0×1.2 m on the west side). Additional shell elements were placed in four of the window openings to simulate their actually being filled in. The physical constants used for the first Princeton model (see note 13) were also employed here.

16 Tests were conducted during the summer of 1989.

Conclusion

The advent of modern computer technology has extended the range of structural analysis so that it is now possible to undertake the type of model study advocated in this essay. Yet Rowland Mainstone's concern about the appropriateness of applying the new engineering methods to the study of historic buildings is valid because "masonry structures like Hagia Sophia do not behave in the same manner as modern structures of steel and concrete . . . [and hence] the interpretation of what happened in the past calls for a different approach from that appropriate to the design of a new structure."[17] Indeed, it is precisely this concern for suitable interpretation of the behavior of historic buildings that makes the integration of the numerical model results with data gathered from on-site tests and archaeological observation so meaningful.[18]

To date, we have begun only the first phase of a full study of Hagia Sophia. But it is hoped that the reader can glean, even from these beginnings, the potential of the approach both for historical inquiry and for questions of restoration, including the protection of this singular monument against future earthquakes.

17 Mainstone, *Hagia Sophia*, 264.

18 During the fall of 1990, the dynamic behavior of the *full* structure (at low amplitudes) was established from a series of ambient vibration measurements taken at different locations within Hagia Sophia (forthcoming in *Civil Engineering*). Measured mean frequencies for the actual structure compared quite favorably with results from a more complete (than described in this essay, but still linear–elastic) model: 1.8 Hz for the first (east–west) mode (vs. 1.97 Hz from the model), 2.1 Hz for the second (north–south) mode (vs. 2.09 Hz from the model), and 2.4 Hz for the third (rotational) mode (vs. 2.38 Hz from the model). As mentioned, nonlinear behavior is expected under higher earthquake-level forces.

THE ROTUNDA OF THESSALONIKI: SEISMIC BEHAVIOR OF ROMAN AND BYZANTINE STRUCTURES

GEORGE PENELIS, MARIA KARAVEZIROGLOU, KOSMAS STYLIANIDIS, AND DEMITRIOS LEONTARIDIS

This essay outlines the seismic behavior of the Rotunda of Thessaloniki, one of the most significant domed monuments of the Late Roman and Early Byzantine periods to have survived to the present, and discusses the consequences of its behavior over the centuries, particularly after the earthquake of 20 June 1978, which pushed the Rotunda to the limits of the collapse. The essay also describes the structural interventions, based on analysis of the monument's seismic behavior, carried out after 1980.

Perhaps a discussion of the Rotunda of Thessaloniki seems irrelevant to the subject matter of this book, which focuses on the structure of the Hagia Sophia of Justinian. However, we consider a critical approach to the structural behavior of and interventions to a building that has survived in an area of high seismic risk for more than sixteen centuries a positive contribution. In fact, since one of the main concerns of the book is the seismic behavior and protection of the Hagia Sophia of Justinian, it is hoped that this essay will generate similar ideas about the methodology to be adopted in the case of the Hagia Sophia.

Description

The Rotunda was built close to, and as a part of, the Imperial Palace in about A.D. 300. It was an imposing circular building resembling the Pantheon in Rome and covered by a huge dome 24.5 m in diameter. The chief difference (apart from the smaller size) was that the construction techniques were typical of those in this part of the Eastern Empire rather than those prevalent in early-second-century Rome. Figure 81 illustrates how eight barrel-vaulted niches lightened its 6.25-m-thick walls.

The original structure has survived substantially intact, as shown in Figures 82 and 83, although it has undergone a number of adaptations.[1] Built

1 G. G. Penelis et al., *The Rotunda of Thessaloniki, Structural Restoration,* 3 vols. (Thessaloniki, 1980; in Greek). G. G. Penelis et al., "Repair and Strengthening of the Monument ROTUNDA in Thessaloniki," National Report of Greece to UNDP/UNIDO, Project RER/79/015 (Thessaloniki, 1982); UNDP/UNIDO, *Repair and Strengthening of Historical Monuments and Buildings in Urban Nuclei. Case Study: The Rotunda of Thessaloniki,* vol. 6 (Vienna, 1984). G. G. Penelis et al., "Repair and Strengthening of the Rotunda, Thessaloniki." Paper presented at the International Symposium on the Restoration of Byzantine and Post-Byzantine Monuments, Thessaloniki, December 1985. G. G. Penelis, "The Masonry of Roman and Byzantine Monuments in Greece," National Report of Greece to UNDP/UNIDO, Project RER/79/015, (Thessaloniki, 1982).

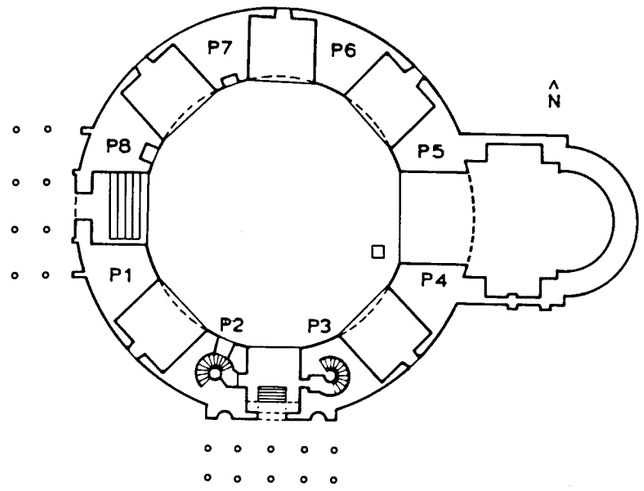


Fig. 81. The Rotunda of Thessaloniki; plan at ground level.

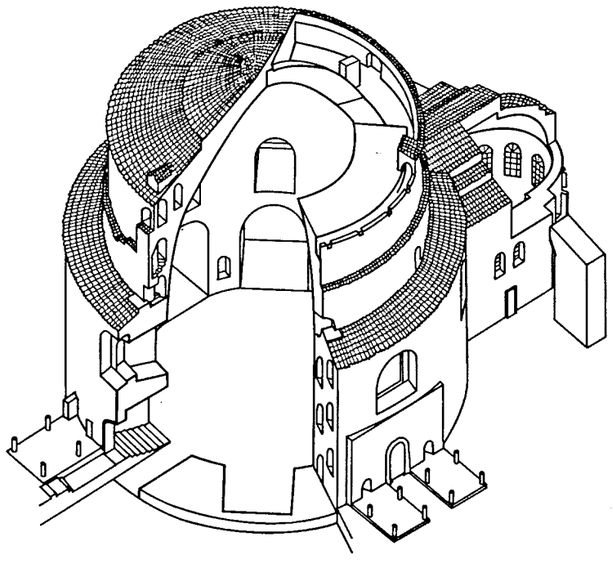


Fig. 82. Cutaway isometric view from the southwest.

first as a mausoleum or a throne room, it was adapted in about A.D. 400 for use as a church. A vaulted chancel, apse, and ambulatory were added. The walls of the niches were pierced to give access to the ambulatory, and the

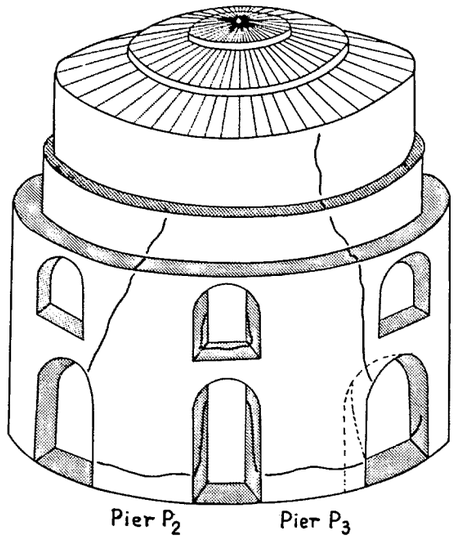


Fig. 83. The main sliding cracks on the southern piers P2 and P3.

main cylindrical wall was cut further at the east to open the interior to the new chancel (see Figure 81). This last intervention seems to have led to a partial collapse of the dome and its subsequent reconstruction. The dome was given a mosaic decoration of saints standing against an architectural background, which has largely survived.

Later, the ambulatory was damaged, perhaps partly by earthquakes. It was removed during the Ottoman occupation, when the church became a mosque. At this time the pierced walls of the niches were again closed, and a minaret, which still stands nearby, was added.

Structural Condition

Before the earthquake of 20 June 1978 (epicenter at Lake Volvi, 30 km from Thessaloniki, magnitude 6.2 on the Richter scale, maximum ground acceleration in Thessaloniki 135 cm/sec^2), the structure was already extensively cracked, especially in the piers (P2 and P3 in Figure 81) that flank the southern entrance and that were already weakened by the helical staircases within them. The inclined cracks in these piers appear to have had a width of about 120 mm, as indicated by tile and mortar fillings probably dating from the beginning of this century. These cracks widened an additional 25 mm over the eight decades before 1978.

Concern over the poor structural condition of the Rotunda was expressed in several reports from 1976 onward, but no action was taken when the earthquake of 20 June 1978 caused further damage, including further opening of the cracks. Unfortunately, the absence of measurements before this earthquake precludes a quantitative estimation of the damage caused. But what is certain is that since the earthquake, the monument has shown a tendency to collapse. The main crack at piers P2, P3 widened 1 mm per month, indicating

that the part of the dome bound by piers P2 and P3 had begun to slide slowly.

(a) *The southern piers P2 and P3.* The cracks in these piers extended over the full height of the monument. As seen in Figure 83 they ran almost vertically up to the outer surface, and they continued, where visible, through the thickness of the piers at an angle of about 70 degrees to the horizontal.

This picture of the cracking, together with soil exploration and static analysis, has led to the conclusion that this was a case of shear-compression failure, which led to the formation of a sliding surface along which the part of the monument bound by piers P2 and P3 tended to slide.

(b) *The northwestern pier at the left of the western entrance.* This pier had a vertical crack near the middle, which extended on both the outer and inner faces up to the springing level of the dome.

(c) *The dome.* This was cracked radially in its lower part in a manner that would be expected from the cracking and associated inclinations of the piers.

(d) *The walls and vaults of the Christian chancel and apse.* In this part of the monument there were cracks along the crown of the vault associated with the outward inclinations of the walls. There were also radial cracks above the windows of the apse, extending up to the springing level of the semidome of the apse, associated also with the outward inclination of the wall of the apse.

Emergency Repairs

Because of the apparently serious structural condition after the earthquake, and to permit further systematic investigation and full consideration of a scheme for final repairs and strengthening, emergency repairs were undertaken as follows:

- erection of heavy-timber shoring between piers P1 and P2, P2 and P3, and P3 and P4, to support the load from the dome directed toward piers P2 and P3;
- erection of shoring on all sides of Piers P2 and P3 to prevent their collapse;
- internal cross-bracing, with heavy timber, of the helical stair openings in piers P2 and P3;
- installation of prestressed external rings of 26-mm-diameter mild steel bars to further assist in preventing continued outward movement of piers P2 and P3;
- support of the chancel vault by metal frames;
- shoring of the south porch; and
- erection of steel scaffolds, both inside and out, to provide access for detailed measurements and, later, for final repairs and strengthening.

Research Methods

Objectives and Research Program

The extensive investigations that then began progressed from architectural and constructional surveys and other in situ surveys and measurements to laboratory tests and analyses of the current stability of the structure. These

investigations were aimed not only at assessing the need for repair and strenghtening, but also at choosing materials and methods appropriate to the character of the monument and its historical importance.

Hence, the research activities with respect to damage evaluation and assessment, the determination of damage sources, and structural intervention covered three main areas: in situ investigations, laboratory tests, and structural analyses.

In Situ Investigations

Architectural and Constructional Surveys

A precise architectural survey was made using standard survey techniques, including photogrammetry.[2] To determine the foundation conditions, four sections were cut to base level. Ten further cuts were made to determine the thicknesses and construction of the dome and the vaults of the Christian chancel and apse. Other details of the construction were determined (or inferred) from observations of the visible surfaces and by comparison with contemporary, partially ruined structures, such as the Palace octagon in the Hippodrome, where similar masonry could be seen on the outer faces.

Survey and Recording of the Damage

An initial survey was made of the lines of all cracks visible on the surfaces of the masonry, both by measurement and photographically. Crack widths and depths (where ascertainable) and relative displacements of the edges (both tangential and normal to the surface of the masonry) were recorded.

Subsequent movement at the cracks was then recorded by means of suitable gauges installed at all critical positions. These continuing measurements served both to indicate any worsening of the structural condition and as a control on the effectiveness of the strenghtening measures. The survey also included measurements, at several levels, of the deviation of the piers from the vertical.

To give a more comprehensible overall picture of damage, the cracks were marked on the transparent Plexiglas model of the structure to a scale of 1:100. Here it was possible to show clearly how cracks visible on the outside related to those inside.

Sample Taking and In Situ Tests on Structural Materials

In order to determine the mechanical properties of the monument in the laboratory, nineteen cores of 10 cm diameter were taken from various locations

2 UNDP/UNIDO, *Repair and Strengthening of Historical Monuments;* G. G. Penelis et al., "Strengthening of the Rotunda Monument in Salonica." Paper presented at the IABSE International Symposium, Venice, January 1983; G. G. Penelis et al., "Materials Used in the Restoration of Historical Buildings and Monuments." Paper presented at the International Seminar on Repair and Strengthening of Historical Buildings and Monuments, held by the Engineering Association of Portugal, Lisbon, 1989.

Table 6. *Strength and Modulus of Elasticity of Construction Materials*

Material	Compressive strength: Mean value (MPa)	Compressive strength: SD (MPa)	Dynamic modulus of elasticity (MPa)
Roman mortar	2.876	0.65	1.890
Christian mortar	3.814	1.25	2.840
Roman bricks	13.120	2.33	10.700
Christian bricks	10.209	2.97	6.000

on the monument (Roman and Christian). From this limited number of specimens, credible values cannot be inferred for the mechanical properties of the whole structure. On the other hand, an unlimited number of cores could not be taken because of the risk of causing extended damage to the monument. Therefore, the cores were combined with nondestructive, wide-range hammer tests (600), as well as ultrasonic measurements (300), which were extended to the whole surface of the monument: mortar and brick, both internal and external. The correlation of hammer testing to corresponding compressive strengths found in the laboratory, through destructive testing, was found to be very satisfactory (867).

The correlation of ultrasonic measurements to corresponding compressive strengths determined through destructive testing at the locations of core taking did not provide satisfactory results (500). Hence, it was not possible to correlate compressive strengths to the ultrasonic measurements. Nevertheless, ultrasonic measurements have given very good correlation for the dynamic modulus of elasticity; therefore, these measurements were used in the statistical evaluation of the dynamic modulus of elasticity of the monument, a quantity indispensable to the analysis as well as to the choice of grout used in the repair. The statistical evaluation of the mortar and brick strengths and dynamic moduli of elasticity is given in Table 6. It can be seen from this evaluation that

- the mean strength of the mortar in the Christian part is considerably higher than that in the Roman part, although it also has, proportionally, higher variability;
- by contrast, the mean strength of the bricks in the Roman part is considerably higher than that in the Christian part; and
- the standard deviations of the strengths of materials of the Christian period are higher than those of the Roman period.

The core materials were also used in the chemical analysis to determine the composition of the monument's structural materials.

Natural Period and Degree of Damping of the Monument's Dynamic Response

To determine the natural period of the monument, ambient vibration measurements were carried out in cooperation with the Laboratory of Engineering Seismology and Aseismic Structures, National Technical University in

Athens. These measurements indicated a natural period of $T=0.42$ second in a radial direction.

It was considered to undertake forced vibration tests before the structure had been repaired and strengthened. Damping was therefore estimated from data on other structures to be $\xi=0.1$. The measurements were recently repeated, just after the structural restoration had been completed. The new measurements were carried out in cooperation with the Seismological Institute of the University of Thessaloniki. The new natural period of the monument in the radial direction has been reduced to $T=0.36\pm0.5$ second.[3]

Soil Borings

Data for the soil on which the monument stood were necessary for the estimation of seismic base shear. These tests also confirmed that the soil conditions exerted no unfavorable influence. Four borings were made, and soil samples were taken for laboratory tests. Standard penetration tests were also conducted.

Laboratory Tests

Chemical Analyses

The chemical analyses were carried out in the Building Materials Laboratory of the Civil Engineering Department at the University of Thessaloniki and had the following aims:

- determination of the proportions between the paste and the aggregates in the construction mortar;
- determination of hydraulic elements in the mortar, particularly in the case where hydraulic elements existed, their quantitative determination and origin, that is, whether they were due to the addition of pozzolanic ash or to the brick powder;
- determination of the composition of the structural bricks and, more specifically, whether they were of the same composition as the mortar's brick powder and had incorporated hydraulic materials; and
- chemical analysis of the materials that could possibly be used for the composition of grouts, for example, hydrated lime, pozzolanic ash, cement, and brick powder.

Mechanical Properties of the Structural Materials of the Monument

Using the cores taken from two parts of the monument, the Roman and the Christian, mortar specimens were prepared in the Laboratory of Reinforced Concrete at the University of Thessaloniki, with dimensions as prescribed by

3 G. Leveldakis and G. Penelis, "Ambient Vibration Measurements on the Rotunda after the Structural Restoration. Evaluation Results." Unpublished manuscript, 1990.

the codes; and flexural and comprehensive strength, the modulus of elasticity of the mortar, and the bond strength between the bricks and the mortar were determined.

Brick specimens were also prepared, and the brick compressive strengths as well as moduli of elasticity were determined. As already mentioned, the number of specimens was limited and used for the calibration of the nondestructive testing instruments. From the laboratory tests, completely reliable data were provided concerning the structural materials – especially the mortar necessary for the preparation of the grouts.

These data were also used for the indirect determination of the compressive strength and modulus of elasticity of the compound masonry, using semiempirical relationships established by current codes. The final results on strengths and moduli of elasticity of original materials are given in Table 6.

Mix Design of the Grouts and Testing of Their Properties

Based on the chemical analyses and tests of the mechanical properties of the monument's mortars, a determination of the composition of grouts was attempted at the Laboratory of Reinforced Concrete, University of Thessaloniki, using traditional materials with mechanical properties compatible with those of the original mortar of the monument.[4] The materials used were the following: hydrated lime, pozzolanic ash, brick powder cement, fine sand, and additives.

Soil Tests

Both the borings and the laboratory tests of the soil samples were carried out at the Laboratory of the Ministry of Public Works. The tests included sieve analysis of the soil samples, determination of liquid and plastic limits, determination of strength in unconfined compression, consolidation tests, and the other routine tests of soil mechanics. Together with the standard penetration tests (SPT), the soil profile and the determination of the water level provided very useful data for evaluating the influence of soil conditions on the damage to the monument, as well as for assessing the influence of local conditions on the base shear of the monument. Some of the soil properties are as follows:

Soil description: very stiff inorganic sandy clay (CL)
SPT: >50
W_p–W_c–W_L: 12%–17%–34%
Angle of internal friction: $\phi=15$ degrees
Unconfined compressive strength: $q_u=0.4$ MPa
Compression index: $C_c=0.07$

4 Penelis et al., "Repair and Strengthening of the Monument ROTUNDA"; UNDP/UNIDO, *Repair and Strengthening of Historical Monuments;* Penelis et al., "Materials Used in the Restoration"; C. Ignatakis, E. Stavrakakis, and K. Stylianidis, "A Special F. E. Axisymmetrical Model for the Analyses of Interventions in Domes Including Cracking Consideration," in *Proceedings of the International Technical Conference on Structural Conservation of Stone Masonry,* Athens, 1989 (Rome, 1990).

Structural Analysis

The ideal approach to the problem would have been the analytical calculation of the historical time-inelastic response of the monument to dead loads and to soil excitation caused by a series of probable accelerograms, using the finite-element method. However, twelve years ago, such an approach to the problem seemed, as it does even today, for reasons mentioned later, to be unrealistic:

- The solid-state discretization of such a complicated, huge and massive structure is very difficult to achieve.
- Reliable stress–strain inelastic triaxial relations cannot be easily adopted since the masonry is a unilateral and orthotropic structure with varying orthotropy and material properties almost from point to point. In addition, the descending branch in the stress–strain constitutive law, necessary for cycling loadings, cannot be justifiably estimated.
- The adoption of a reliable strength envelope varying from area to area of the structure cannot be supported by experimental evidence when the independent variables are not only the stresses σ_1, σ_2, σ_3, but also the direction cosines of the masonry orthotropy (direction) of the bed joints.
- The loading path, which plays an important role in inelastic analysis, cannot be easily estimated for a monument dating back centuries.
- The existing cracks due to foundation settlement, various restraints, and past accidental actions (i.e., earthquakes) cannot be taken easily into account in the analysis of the existing structure and, moreover, cannot be reproduced analytically in the successive loading steps up to failure.
- It is very difficult to adopt reliable accelerograms to the dynamic analysis of the monument when the existing information on this matter is limited to the past forty or fifty years.

Taking all of these uncertainties into account, it seems fairly meaningless for practical purposes to attempt a sophisticated analysis using modern general-purpose finite-element modeling programs or even problem-oriented finite-element modeling programs (such efforts carried out in our laboratory will be presented later). In fact, when so many parameters of the problem are uncertain and the output results are so sensitive and highly dependent on these parameters, these results cannot be considered reliable.

Bearing all this in mind, we think that in order to determine the residual load-bearing capacity of a masonry monument, the following procedure should be adopted:

- In principle, the structural analysis of a monument that has survived for centuries is necessary only when signs of failure, such as detectible deformations and settlements, appear in its structure. There is no better index of the structural efficiency of a monument than the fact that it has survived for centuries without structural defects.
- Hence, with the crack pattern and deformations of the structure as a guide, we determine the expected failure mechanism either by using the step-by-step method or the theorems of plasticity for the upper and lower bounds.
- For this failure mechanism we determine the ultimate load of the structure.

Table 7. *Strength and Modulus of Elasticity of Original Masonry*

	Comprehensive strength nominal value (MPa)	Tensile strength nominal value (MPa)	Bond strength nominal value (MPa)	Modulus of elasticity mean value (MPa)
Roman part	2.5	0.3	0.3	2,450
Christian part	2.5	0.3	0.3	3,100

The ratio of the ultimate to service load is a reliable index of the level of the structure's overall safety.
- The elastic or inelastic analysis reveals one of the probable stress states of the monument, useful for the verification of the existing crack pattern under service loads.
- The extrapolation of the results of elastic or even inelastic analysis to the ultimate state should not be considered reliable if the resulting failure mechanism does not comply with the existing crack and deformation pattern of the monument.

Evaluation of the Mechanical Characteristics of the Structure

Strength and Stress–Strain Relations of the Masonry. The bearing capacity and modulus of elasticity of the initial masonry must be determined before any analysis can take place. The usual procedure is to examine bricks and mortar samples individually (as presented in the preceding section) and then to calculate from these results the load-bearing capacity and the modulus of elasticity of the masonry using various semiempirical formulas for analytical methods. This procedure was followed for the Rotunda as well.[5] The resulting values are given in Table 7.

For Poisson's ratio, an estimated value from the bibliography was used; that is $\nu = 0.19$. Since failure was possible in shear and compression, it was necessary to establish failure criteria for the masonry in combined compression and shear. The tests referred to under "Mechanical Properties of the Structural Materials" and the procedures just mentioned gave only the uniaxial compressive strength, the bond strength between bricks and mortar, and the uniaxial tensile strength (given indirectly by the bending strength of the mortar). An envelope of ultimate strength in combined shear and compression was therefore obtained from the analogy of the curves of low-strength concretes having similar compressive and tensile strengths, as shown in Figure 84 (referred to as conventional).

Recently, extensive research has been carried out to find a better approach to the problem of evaluating the mechanical properties of masonry, either by

5 Penelis et al., "Repair and Strengthening of the Monument ROTUNDA", UNDP/UNIDO, *Repair and Strengthening of Historical Monuments;* Penelis et al., "Repair and Strengthening of the Rotunda."

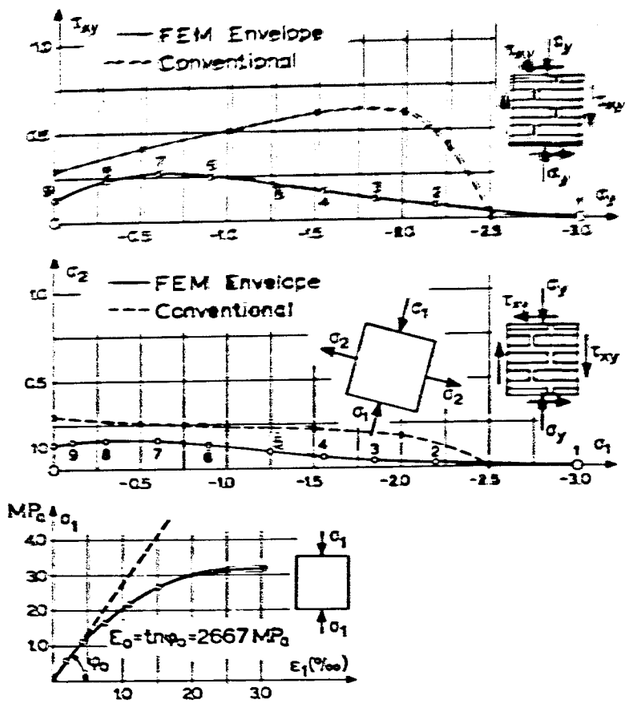


Fig. 84. The τ_{xy}–σ_y and σ_1–σ_2 envelope of the original masonry and the respective σ_1–ϵ diagram (FEM, finite-element model).

means of partially destructive methods[6] or by means of finite-element modeling.[7] We believe that the analysis by means of finite-element modeling with microelements of mortar and brick is the most promising one for the determination of the failure envelope (τ–σ, σ_1–σ_2 curves) and the constitutive law of old masonries, since the necessary input is the geometry of the masonry and the mechanical properties of the bricks and the mortar; that is, compressive strength f_c, tensile strength f_t, initial modulus of elasticity E_0, Poisson's ratio ν, bond strength T_c at the bed joints, friction coefficient θ at the bed joints, and ultimate deformation ϵ_{1u}. The results of an analysis of this type carried out recently in our laboratory are given in Figure 84 for comparison.[8]

Natural Period, Damping, and Ductility. The first natural period of the monument, necessary for the evaluation of the seismic coefficient, was determined analytically by means of the Rayleigh method. Two different mechanical models were used. The first was a series of free cantilevers with rings at

6 F. Berger, "Assessment of Old Masonry by Means of Partially Destructive Methods," in *Proceedings of the International Conference on Structural Repairs and Maintenance of Historical Buildings*, Florence, 1989 (Southampton, 1989).

7 C. Ignatakis, E. Stavrakakis, and G. Penelis, "Analytical Model for Masonry Using the F.E.M.," in *Proceedings of the International Conference on Structural Repairs and Maintenance of Historical Buildings*, Florence, 1989 (Southampton, 1989).

8 C. Ignatakis, E. Stavrakakis, and G. Penelis, "Inelastic Analysis of Masonry Monuments and Historical Buildings by Means of Finite Element Modelling." Unpublished manuscript, 1990.

midheight that vibrate radially and simultaneously. This model simulates the behavior of the piers, given that the upper ring supporting the dome is extensively and radially cracked. The second was a free cantilever pier. The analytical results of these two models were found to be in very good agreement with the in situ ambient vibration measurements: $T_{\text{free cantil.}} = 0.53$ second; $T_{\text{ambient vibr.}} = 0.42$ second; $T_{\text{ring + cantil.}} = 0.33$ second. The degree of damping for the monument was estimated from other structures to be $\xi = 0.10$. The relevant ductility factor form estimating the seismic loading was the one associated with outward rotations of the piers. This was determined both for free cantilever action and for analytical models in which rotation of the piers was restrained by prestressed rings of various types of steel at the levels of the rings installed in the emergency repairs. The resulting ductility values for various cases of steel rings are

free cantilever: $\mu = 4.46/1.5 = 2.97$
steel rings ST 22/34: $\mu = 4.46/1.7 = 2.62$
prestressed steel rings ST 22/34: $\mu = 4.46/1.25 = 3.57$
prestressed steel rings ST 42.70: $\mu = 4.46/1.25 = 3.57$

Estimation of Seismic Loading. Taking into account the seismic risk analysis of the region and using the aforementioned data on soils, natural period, damping ductility, and importance of the monument, the seismic loading was estimated according to the Greek Code (in preparation at that time), the SEAOC Code, and the response spectrum derived from the accelerogram of the 1978 Thessaloniki earthquake. This approach resulted in a value of the base shear due to earthquake ranging from $V = (0.11 - 0.14)W$, where W is the dead load of the monument. Finally, the value $V = 0.12W$ was chosen, which helped in the estimation of the ultimate shear strength of the massive piers of the monument that have not failed for seventeen centuries.

Static Analysis of the Roman Part of the Structure

Initially, several elastic analyses were made for

- vertical gravity loading,
- independent ring-type loadings at three levels where there was a possibility of installing permanent peripheral prestressed rings, and
- horizontal seismic loading.

The structure as a whole was analyzed first, using an axisymmetric finite-element model. The presence of the niches in the cylindrical lower part of the structure was allowed for by introducing a reduced modulus of elasticity there. Stresses in the dome, as calculated in one of these analyses, are plotted in Figures 85 and 86.[9]

The support system of the dome was then analyzed as a linear-element space frame (Figure 87). For this purpose the forces at the junction of the dome and the supports were taken from the previous analysis, except in the case of horizontal seismic loading. In that case, because of their relative un-

9 Ignatakis et al., "A Special F. E. Axisymmetrical Model."

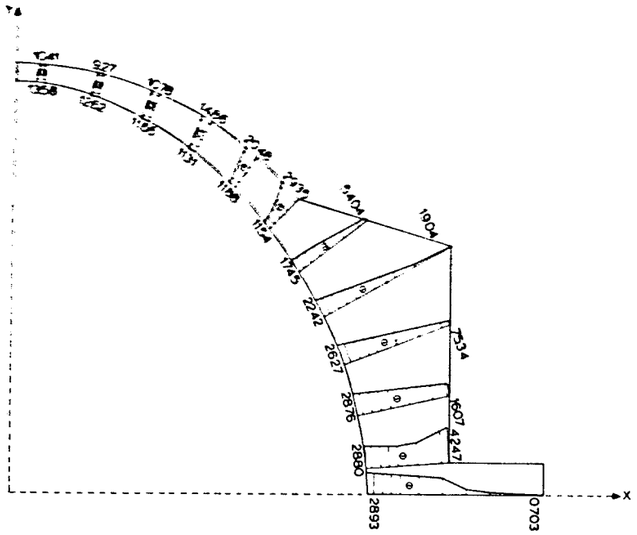


Fig. 85. Calculated distribution of the meridional stresses in the dome without taking into account the meridional cracks.

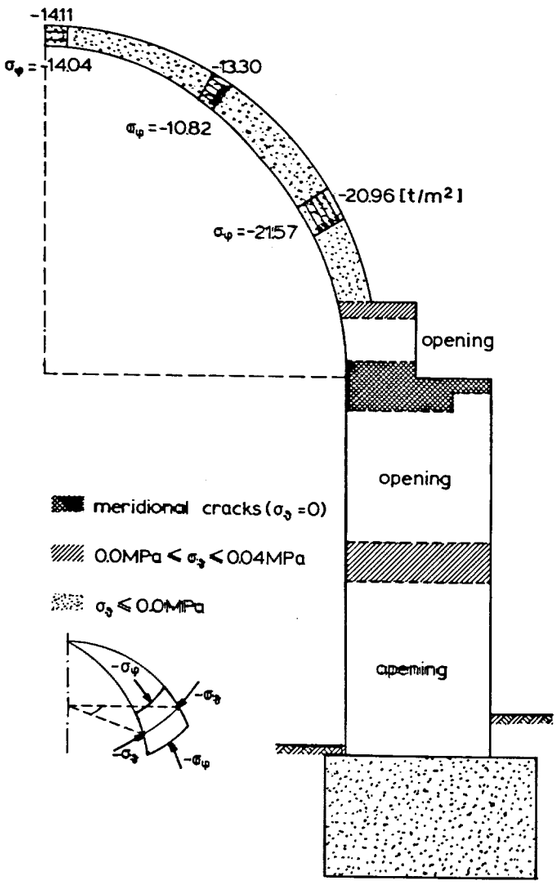


Fig. 86. A recent elastic analysis of the Roman part using finite-element modeling and taking into account the meridional cracks and the openings.

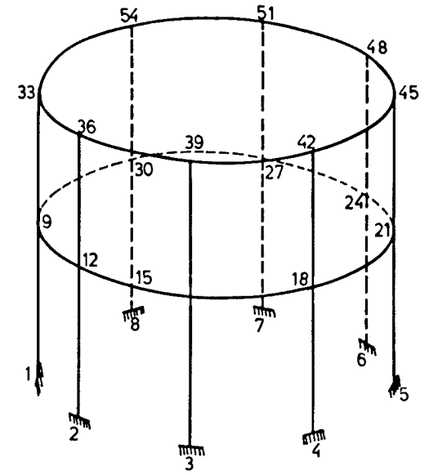


Fig. 87. Frame model of the dome support system.

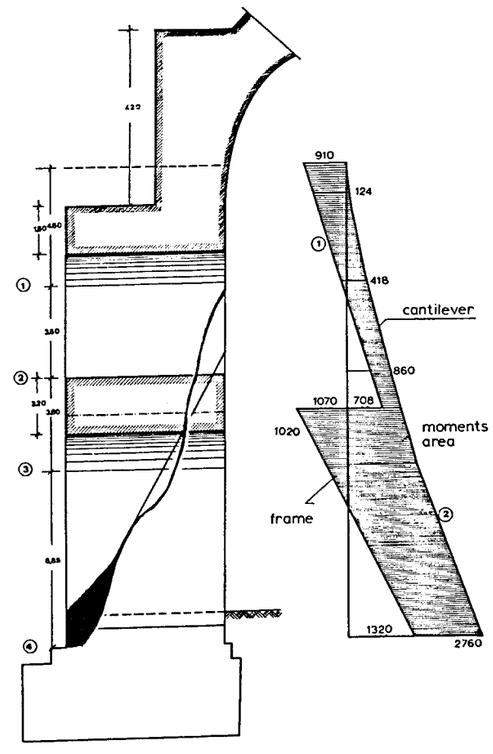


Fig. 88. Cracked pier with staircase and corresponding moment diagram.

importance for the shell itself, they were estimated by the simpler membrane theory. This analysis was performed both for the initial state of the structure with an uninterrupted supporting ring at the intermediate level in the east and for the later state with the ring cut here to give access over its full height to the Christian chancel.

Elastic analyses, however, provide only conservative estimates of collapse loads. In fact, in this case, where the structure is composed of masonry that has a limited and unreliable tensile strength, the two rings (the one supporting the dome and the intermediate one) suffer from early cracking and interruption of continuity for very low loads – just above the working loading level – without implying that the load-bearing capacity of the structure has been exceeded, since the piers, acting as cantilevers, possess reserves of extra load-bearing capacity. Both for this reason and because such analyses are of questionable validity when the structure is already extensively cracked, ultimate load analyses were also made.

Application of the upper- and lower-bound theorems led to the conclusion that the collapse mechanism would involve interruption of the continuity of the rings and masonry linking the piers and the formation of hinges at the top and bottom of the piers. Ultimate loads were therefore calculated for the piers acting as free cantilevers (Figure 88).

Using as data the stress state of the dome and the M, N, Q diagrams of the supporting structure the following superpositions were performed:

- Dead load on the monolithic structure before the cutting of the intermediate linking ring in the area of the chancel;
- Dead load on the monolithic structure after the cutting of the intermediate ring in the area of the chancel;
- Dead load plus 12 percent seismic base shear on the monolithic structure before the cutting of the intermediate ring;
- Dead load plus 12 percent seismic base shear on the monolithic structure after the cutting of the intermediate ring;
- Ultimate dead loads on the piers acting as free cantilevers; and
- Dead load plus ultimate seismic base shear on the piers acting as free cantilevers.

Conclusions Concerning the Roman Part of the Structure

Superstructure. From these analyses, the following conclusions were drawn about the structural behavior and safety of the structure at different times:

- As first constructed, all structural members had a safety factor under gravity load within the range of about 2.70 to 3.10. Thus, they had fairly uniform strength at all critical points, similar to that which would be provided today for masonry construction under seismic plus gravity load. However, ruptures of the upper and lower rings between the piers were already possible and may have occurred in this initial state.
- After the cutting of the intermediate ring in the east for the Christian chancel, a rupture of the upper ring was possible even under gravity load if it had not already occurred, and this would have led to a partial collapse of the dome.
- Additional siesmic load at this stage would certainly have caused rupture of the upper ring.

The Christian modification critically reduced the structure's load-bearing capacity, and it is certain that, at least after the next strong earthquake, the

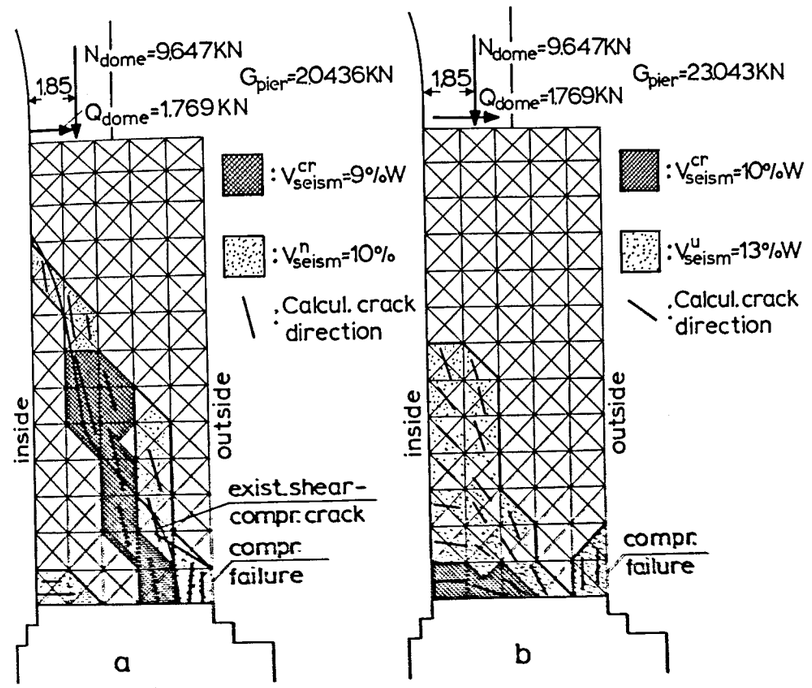


Fig. 89. Predicted failure pattern of the piers of the Roman part using an inelastic finite-element model analysis: (a) cracked pier with staircase; (b) uncracked massive pier.

piers would have had to act as free cantilevers. Thus, the subsequent behavior need be considered only on this basis. The following further conclusions were drawn about the piers when so acting:

- Gravity load could be carried with a safety factor of about 2.15.
- Under gravity plus seismic load, piers P2 and P3 should fail in shear from a crack inclined at 61 degrees to the horizontal for a base shear due to earthquake with a lower bound of about 8.5 percent of the gravity load (Figure 88). As can be seen in Figure 88, this calculated crack inclination agreed closely with the measured inclinations of the observed cracks in these piers. The remaining piers (which are not weakened by internal stairs) should safely withstand a roughly 70 percent greater base shear due to an earthquake (13.5 percent of the gravity load). This is consistent with the observed lack of damage and the estimate of a base shear of $V_R = 0.135W + V_{\text{dome + thrust}}$.
- Failure of piers P2 and P3 activated the sections of infill wall of the flanking niches, and these prevented complete collapse of the piers by raising the combined seismic shear resistance to about 14 percent of the gravity load.
- The addition of the temporary prestressed rings significantly improved the safety margins.

For comparison, we shall present the results of a finite-element model inelastic analysis of the two types of pier (Figures 89a and b) carried out by

means of a computer program developed in our laboratory.[10] This analysis was performed with the failure envelope $\sigma_1-\sigma_2$ and the curve illustrated in Figure 84. This procedure, in spite of the drawbacks presented under "Structural Analysis," seems to have good prospects for further development. In fact, the failure pattern and the crack inclination of the weakened pier with the internal staircase, as determined analytically by this procedure, are in very good agreement with the real picture of damage. Furthermore, the base shear resistance of both types of pier was found to be very close to that found through the shear compression model twelve years ago: $V_R=0.10W+V_{\text{dome thrust}}$ for the weakened piers and $V_R=0.13W+V_{\text{dome thrust}}$ for the regular piers. Of course, many points and results should be justified through extensive parametric analyses before this procedure can be considered a useful practical tool.

Foundations. On the basis of the soil investigation, the in situ survey of the foundation, and the computed stresses and deformations, the following conclusions were drawn in reference to stresses:

- For dead loads, no eccentric action has been determined at the foundation level. The uniform compressive strength was calculated to be 0.3 MPa, a value well below $\sigma_{perf}=0.6$ MPa, which was based on the soil tests.
- For a seismic action corresponding to $V=0.12W$ a small inactive area existed at the soil level with a maximum stress at the outer boundary of the foundation equal to 0.79 MPa, which is within the permissible limits.
- Finally, the ultimate seismic load that could be carried by the foundation before the strengthening of the monument was found to be $V=0.185W$, which is greater than the ultimate seismic strength of the superstructure before the strengthening.

It was further concluded that the calculated stresses in the foundation were well within safe limits throughout the life of the structure. Since the addition of the circumferential prestress improved safety, there was no need for further checking of the foundation for the state of the monument after the intervention.

The following conclusions were drawn in reference to deformations:

- Although a satisfactory factor of safety for the stress state due to dead loads was found, it was also discovered that in spite of the good quality of the soil, a settlement of the order of 10 cm occurred during the lifetime of the monument. This value lies within the limits permitted today for brick masonry structures.
- For a seismic loading corresponding to $V=0.13W$, determined as the ultimate seismic shear-bearing capacity of the massive piers before strengthening, it was found that the tops of the piers had undergone an outward displacement of 5.0 to 12.0 cm depending on the structural system considered in the analysis. The in situ measurement verified these values.
- Combining the analysis of the superstructure with that of the foundation, it was concluded that the considerable width of the radial cracks is due mainly to the rotations of the foundation ring, caused by various seismic actions that have occurred in the past.

10 Ignatakis et al., "Inelastic Analysis."

Static Analysis and Conclusion Concerning the Christian Chancel and Apse

The analysis of the Christian part was performed using a step-by-step ultimate load method described later. Failure criteria for the cross sections of the piers and the vault were first plotted as interaction curves between moment (M) and normal (N) and between normal stress (σ) and shear stress (τ), derived from the following assumptions:

- the tensile strength is equal to the estimated flexural strength;
- the compressive strength is equal to the estimated overall strength of the bricks and mortar; and
- behavior in the compressive–tensile $\sigma_1-\sigma_2$ zone is similar to that of a low-strength concrete.

It is quite clear that in the case of the Christian part the same assumptions as those of the Roman part could be used. Then a step-by-step increase in the dead load was applied to determine the successive plastic hinges until a collapse mechanism was formed.

For response under seismic load, the same procedure is followed up to full service (gravity) load and then continued with increasing horizontal load until a collapse mechanism forms. At each step of the analysis, however, it is necessary to check that no shear failure will occur in the supporting system. This is done by means of the curve representing the ultimate strength of the masonry in combined shear and compression (see Figure 84).

In our case, an initial ultimate load analysis of the chancel according to the procedure just described indicated a factor of safety of about $\nu=67$ percent for gravity load alone. It seemed unlikely that the apse would add sufficiently to the total strength, helping to prevent collapse even without an earthquake. This suggested either that the flying buttresses were erected at the same time as the chancel, or that the present heavy covering of the vault was a later addition and the buttresses were added when this was done. Hence, a further analysis was made in which the flying buttresses were included. This still indicated a low factor of safety ν of about 120 percent for gravity load alone.

It is interesting to follow the formation of the plastic hinges on the structure for dead loads in the step-by-step procedure:

- For 50 percent of the dead loads, the first two hinges are formed on the arch at an angle of 60 degrees, symmetrically from the crown.
- For 81 percent of the dead loads, the next two hinges are formed on the base of the flying buttresses, while simultaneously, a fifth hinge is formed at the crown of the arch.
- Finally, for 120 percent of the dead loads, the two last hinges are formed at the base of the piers and the system is transformed into a kinematic chain. From the description just given it can be concluded that, even at service loads, three zones with cracks should be visible: the crown of the arch from

the inside and the zones at 60 degrees from the outside, a fact that was in compliance with the existing situation before the intervention. For the Christian part of the monument no analysis was made for seismic load, since any analysis for horizontal load that did not include the establishing contribution of the adjacent Roman part and the apse would have been unrealistic.

Proposals for Repair and Strengthening

Proposals for repair and strengthening had to meet the following requirements:[11]

- Repairs should be clearly distinguishable from original work so that the authenticity of the latter would not be placed in doubt.
- Interventions should, where possible, be reversible to permit the adoption of an improved procedure at a later date.
- Where reversible procedures are impracticable, the materials should be fully compatible with the original materials and should be of known long-term durability.

Proposals for the Roman Part

On the basis of the analysis just described, local repair and strengthening of piers P2 and P3 was considered necessary, with more general repair and strengthening by internal grouting and the installation of permanent peripheral prestressed rings.

For the local repairs and strengthening of piers P2 and P3, the following were proposed:

- The application of an internal reinforced concrete (gunite) skin to each helical stairway, using as reinforcement high-strength deformed bars of an austenetic stainless steel alloyed with chromium, nickel, and molybdenum. This proposal was later modified upon request of the Central Archaeological Council, and the reinforced concrete skin was replaced by a steel cage (reversible intervention), as shown in Figure 90.
- The stitching of the piers throughout their height as shown in Figure 91 using prestressed bars $2\phi 26/1.5$ m, $V=335$ kN/1.5 m of the same steel (high-strength deformed bars ST 420/700 of an austenetic stainless steel) protected by means of a cement grout of high alkali content. The usual prestressing steels were not used because of their sensitivity to corrosion in long-term exposure, on one hand, and the existing difficulties in providing adequate anchorage within the masonry, on the other.

The general proposals for repair and strengthening in more detail include the following:

11 UNDP/UNIDO, *Repair and Strengthening of Historical Monuments;* M. Karaveziroglou, J. Papayianni, and G. Penelis, "Criteria for Selecting Materials for Repair Brick Masonry." Paper presented at the International Technical Conference on Structural Conservation of Stone Masonry, 335–42, Athens, 1989. Penelis et al., "Materials Used in the Restoration."

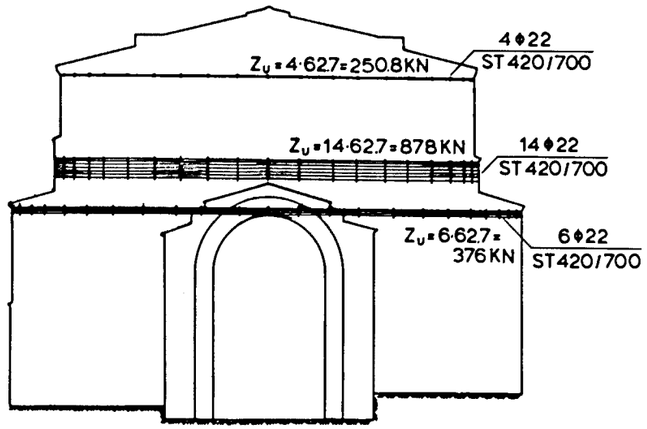


Fig. 90. Reinforcement diagram of piers P2 and P3 of the Roman part.

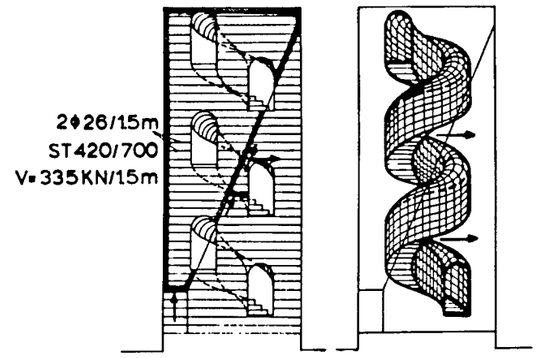


Fig. 91. External elevation of permanent prestressed tie rings in the Roman part.

- The grouting of all cracks in the piers.
- The installation of permanent mild steel (ST 37) rings on the face of the monument, as shown in Figure 91. These rings should be protected by a lead coating (reversible intervention). The lead-coating mild steel was proposed for three reasons: high resistance to atmospheric corrosion in long-term exposure, low cost, and limited risk of relaxation even for low prestressing stresses due to the age of the structure.

Later, owing to unexpected difficulties in producing lead-coated bars of 6.00 m length in Greece, stainless austenetic steel bars of the type Cr–Ni–Mo (ST 420/700) replaced them.

Additional proposals are as follows:

- The initial stressing of these rings to 50 percent of the final prestress, with the simultaneous removal of the temporary rings.
- The grouting of all radial cracks in the upper and in the intermediate masonry rings.
- The final stressing of the steel rings.

Proposals for the Christian Part

A major weakness has been disclosed in the Christian part in the resistance offered to horizontal thrusts exerted by the vault. The following proposals were aimed chiefly at remedying this weakness:

Alternative A

- the grouting of existing cracks;
- the installation of temporary transverse ties at the springing level of the vault;
- the strengthening of the existing flying buttresses;
- the construction of an additional pair of flying buttresses;
- the removal of the temporary ties;
- the grouting of any fresh cracks; and
- the local strengthening of the apse by prestressed peripheral ties 3ϕ26/ST 420/700, S = 88 kN.

Alternative B

- the grouting of the existing cracks;
- the installation of permanent transverse prestressed ties of stainless austenetic of the type Cr–Ni–Mo, two groups of 230 each, ST 420/700, S = 320 kN; and
- the local strengthening of the apse by prestressed peripheral ties, 3ϕ26 ST 420/700, S = 88 kN.

The Central Archaeological Council approved the second alternative.

Selection of a Suitable Grout

Grouting is an irreversible intervention. This fact ruled out the use of organic resins whose long-term behavior is unknown and favored the use of traditional inorganic materials whose durability was proven in the monument itself. Similar requirements arose in the repair and strengthening of other monuments in Thessaloniki. A whole series of mixes was therefore tested to provide a basis for selecting the most suitable ones for each monument in accordance with the desirable strengths and moduli of elasticity and the current specifications for fluidity, bleeding, shrinkage, and sedimentation.[12]

In the first stage of the test program, the grouts were mixed from hydrated lime and powdered brick, or from hydrated lime, powdered brick, and pozzolanic ash. Although the powdered brick in the Roman mortar had given it good hydraulic properties, the results with powdered brick were unsatisfactory. The final mixes to be tested were therefore ones of pozzolanic ash, hydrated lime, and cement, in ratios varying from 10:5:1 to 10:5:10, and of pozzolanic ash, hydrated lime, cement, and fine sand, in ratios varying from 10:5:1:16 to 10:5:10:15. Tricosal H181 was added to all mixes to limit bleeding and quick setting (and thus to improve fluidity). Water contents were chosen to give a sinking time (according to German specifications) between about 30 and 32 seconds in order to ensure penetration into the cracks. For each mix, specimens were prepared according to current specifications to determine bleeding and sedimentation, shrinkage, flexural strength, compressive strength, bond between bricks and grout, and modulus of elasticity. The strength tests covered periods of up to 9 months. Tests were also made to determine whether the grout could be pumped in by a hand-operated pump. On the basis of these tests, the most suitable grouts were selected.

12 Penelis et al., "Repair and Strengthening of the Monument ROTUNDA"; UNDP/UNIDO, *Repair and Strengthening of Historical Monuments;* C. Siaxavani, "Injections at the Rotunda, Application." Paper presented at the International Symposium on the Restoration of Byzantine and Post-Byzantine Monuments, Thessaloniki, December 1985; Karaveziroglou et al., "Criteria for Selecting Materials"; G. G. Penelis, J. Papayianni, and M. Karaveziroglou, "Pozzolanic Mortars for Repair of Masonry Structures." Paper presented at the International Conference on Structural Repairs and Maintenance of Historical Buildings, Florence, 1989; G. G. Penelis, J. Papayianni, and M. Karaveziroglou, "Grouts for Repairing and Strengthening Old Masonry Structures." Paper presented at the International Conference on Structural Repairs and Maintenance of Historical Buildings, Florence, 1989; Penelis et al., "Strengthening of the Rotunda"; Penelis et al., "Materials Used in the Restoration"; G. G. Penelis, "Seismic Behavior of Masonry in Roman and Byzantine Monuments." Paper presented at the International Symposium on Restoration of Byzantine and Post-Byzantine Monuments, Thessaloniki, December 1985.

Reanalysis and Redesign of the Monument

On the basis of the proposals described in the preceding section for the repair and strengthening of the Roman as well as the Christian part of the monument, a reanalysis and redesign was carried out for each part. The reanalysis involved the overall structural behavior of the structure for the consecutive stages of intervention, whereas the redesign involved the proportioning of the necessary new elements, such as rings, ties, prestressed stitches, and steel cages.

Roman Part

As already mentioned, the reanalysis and redesign were directly related to the methods of intervention. These methods, excluding the repairs of local significance that did not affect the general static behavior of the monument, included the following:

- grouting of all the pier cracks;
- installation of steel rings at two characteristic locations (these rings are prestressed at the first stage up to 50 percent);
- simultaneous removal of the temporary rings;
- grouting of the radial cracks on the upper and intermediate masonry rings of the monument; and
- prestressing the steel rings the remaining 50 percent to full strength.

Consequently, the following superpositions had to be made, partly for the pier cantilever and partly for the monolithic structure.

Dead Loads after the Intervention

The stress state on the monument results from permanent loads and 50 percent of the ring prestressing at the free cantilever piers, plus the stress state of

the monolithic structure due to the remaining 50 percent of the ring prestressing.

From this superposition, which actually gives the stress state of the monument for dead loads after the grouting of the cracks, the installation of the permanent prestressed rings, and the removal of the temporary shoring, it was concluded that the whole structure is under a compressive state of stress with a safety factor of $r=2.58$ instead of $r=2.15$, which was the safety factor of the monument for dead loads before the failure of the piers P2 and P3.

This analysis assumed that the piers P2 and P3 would be repaired and strengthened locally, since they continued to be sensitive to shear compression. The local interventions to the piers mentioned under "Proposal for the Roman Part" were designed for a safety factor $r=2.04$ for the steel stitches, that is, higher than $r=1.75$, which is the accepted safety factor for steel.

Dead Loads and Earthquake after the Strengthening

From this superposition it appears that the overall safety of the monument is high enough. From a more detailed linear analysis at service state for dead loads plus a seismic base shear $V_{service}=0.12W$, it was concluded that the masonry rings (the dome-supporting ring and the intermediate one) seem to be cracked. Hence, it was decided that additional ultimate state analyses should be carried out for free cantilevers, once vibrating in phase (simultaneous outward movement) and once out of phase (antimetric movement).

The first mode is the most favorable for the monument's safety, because owing to the expansion of their diameter the prestressed rings are strained to the yield point and so cause the highest possible inward-directed forces on the piers. The second mode is the most unfavorable for the monument's safety because the prestressed rings remain unchanged during the vibration and so cause the lowest possible inward-directed forces on the piers equal to the initial ones due to prestressing. For these two boundary modes of vibration during an earthquake, the ultimate seismic base shear was evaluated at $V_{ult}=(0.205-0.185)W$ for the massive piers and $V_{ult}=(0.218-0.2)W$ for the piers with helical staircases in their cores, where W is equal to the dead load of the structure.

It should be noted here that the preceding analysis was carried out assuming that piers P2 and P3 had already been repaired locally according to the procedure mentioned under "Proposals for the Roman Part." These local interventions, designed, as was noted previously, for a safety factor $r=2.04$ for dead load W, also secured a shear resistance for piers P2 and P3 capable of carrying the dead plus seismic base shear ranging between $0.4W$ and $0.45W$. It should also be noted that a wide range of control calculations was necessary to secure the safety in various points as anchorage areas, anchorage plates, bolts, inner cage at helical stairs, and so on.

Christian Part

Reanalysis and detailing were again carried out following the provisions of the intervention procedures presented under "Proposals for the Christian Part."

The reanalysis on alternative B, which was approved for execution, is briefly as follows:

- the grouting of the existing cracks;
- the installation of permanent prestressed ties (prestressing force 64 kN, giving 64 MPa); and
- the local strengthening of the apse by prestressed peripheral ties.

The reanalysis was performed using the same step-by-step ultimate load method followed for the analysis of the original structure. This reanalysis indicated a safety factor for gravity loads of $\nu=2.10$.

It is interesting to follow the step-by-step formation of the plastic hinges on the restored structure for dead loads. It should be noted that the structural system did not include the flying buttresses, because it was estimated that, owing to the prestressing ties at the springs of the vault, the existing flying buttresses would be structurally inactive.

- For dead load plus prestressing ties (for the service state after the groutings and the installation of the prestressed ties) the structure shows only two plastic hinges at the arch, 60 degrees symmetrically from the crown.
- For 142 percent of the dead loads, a hinge at the crown is formed again.
- For 180 percent of the dead loads, the ties reach their yielding point (stage 3).
- For 210 percent of the dead loads, the two last hinges are formed at the base of the piers and the system is transformed into a kinematic chain. Of course, there are some extra reserves due to the flying buttresses that would be activated again at this stage, but these were not taken into account.

It should also be noted that for the Christian part, a wide range of control calculations was necessary to secure safety in various points, such as anchorage areas, anchorage plates, and bolts.

Specifications and Execution

When a detailed design had been completed for all the proposals, full detailed drawings and specifications were prepared; these included a technical description of the existing structure and details of the procedures to be followed. The work of repair and strengthening was authorized on this basis in December 1981 and has been completed recently (Figure 92).

Conclusions

In areas of high seismic risk, earthquakes are the predominant cause of damage to and collapse of monuments and historical buildings. For centuries these buildings have periodically suffered strong seismic actions and have undergone a kind of natural selection, so that only those that were well designed and constructed have survived.

Consequently, when structural interventions are made, the original structural system should in principle be kept unchanged. At most, only local repairs or improvement of the original structural behavior should be accepted.

Fig. 92. The Rotunda of Thessaloniki after structural interventions.

No one is by any means in a position to guarantee that a modified structural system will have a better chance than the original of surviving in the following centuries.

In order to estimate the load-bearing capacity of a monument from dead or seismic loads and to make decisions about possible interventions, a complicated procedure of investigations is required. This procedure begins with temporary shoring and installation of scaffolds for approaching the monument and continues with in situ measurements and investigations, laboratory tests, and rigorous structural analyses. Only a thorough knowledge of the properties of the materials involved and the structural behavior of the monument justifies intervention.

The structural research must not be limited to elastic analyses. The low tensile strength of the masonry, the uncertainties about the mechanical properties of the original materials, and the existing cracks and settlement make an ultimate load analysis more reliable. The extrapolation of the results of any analysis to ultimate state should not be considered reliable unless the resulting failure mechanism agrees with the existing crack and deformation pattern of the monument.

In the event that any structural intervention is decided upon, it should be kept in mind that the aim of the restoration is to preserve and reveal the aesthetic and historical value of the monument and is based on respect for original materials and authentic documents. This imposes on the specialists responsible for the restoration a duty to consider what limitations these considerations place on the choice of methods and materials of repair and strengthening. These general principles are embodied in the Venice Charter under the heading "Restoration."

The key to the choice of materials is the classification of the restoration techniques into two main categories: reversible and irreversible. Materials used in reversible interventions usually impose very few restrictions. In contrast, materials used in irreversible interventions impose the following two additional restrictions: compatibility of the new materials with the original ones and very long term durability of the new materials. These restrictions necessitate a thorough knowledge of the properties for the original materials so that they can be used as a guide to the choice of materials for repair and strengthening. It is generally accepted that the best way to satisfy the requirements for compatibility and durability is to choose "traditional materials" for restoration.

Structural restoration is a highly specialized operation, one that calls for the collaboration of specialists in many scientific disciplines such as archaeology, architecture, survey engineering, structural engineering, and chemical engineering, strongly supported by computational methods and well-equipped laboratories.

QUESTIONING HAGIA SOPHIA

ROWLAND J. MAINSTONE

The unique achievement of Anthemius and Isidorus has long inspired wonder and awe and has challenged the understanding of later generations. Of the many questions that it has provoked, this volume considers only three, all related to its structure – questions about design, about structural behavior under environmental loadings over almost fifteen centuries, and about present safety in the face of future earthquakes.

Though I have always sought a wider understanding and found it more profitable to consider purely structural questions alongside others, I shall restrict my comments to them, with the emphasis (at the editors' request) on structural modeling. These comments will include several serious reservations about the finite-element model now proposed and about its adoption without adequate consideration of whether it is the most suitable one for answering the questions posed.

The Structure

Of all the structures that have survived to the present, Hagia Sophia's is possibly the most difficult to analyze. Even its present form almost defies comprehensive visualization and graphic representation, either with or without its many deviations from geometric regularity. To the complexities of form must be added complexities of construction and use of materials, and those resulting from a long history. To a large extent, moreover, the latter complexities are hidden from view behind surface renderings and revetments.

The survey by Van Nice[1] is unmatched in its accurate delineation of the present principal horizontal and vertical sections and elevations, supplemented by two equally precise isometric views. But in a limited number of sheets, much had to be omitted and, even at the generous scales selected for

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1 R. L. Van Nice, *St. Sophia in Istanbul: An Architectural Survey*, 2 vols. (Washington, D.C., 1965 and 1986).

reproduction, some of the accuracy of the basic measurements is inevitably lost. Most construction details and aspects of the present structural condition – materials used, bonds and lacks of bond, cracks and separations – are unrecorded, and it is not always clear to the uninitiated whether the absence of indications of cracks or unbonded joins means that there are none or merely that to have shown them would have been confusing or that none were observed because the working masonry was never open to view. Here especially, the lack of the intended explanatory text is a serious shortcoming.

Most of my own general plans, sections, elevations, and analytical isometrics do not show the present state but the probable intended form in 562 – that is, the form without any unintended deformations – though these drawings are supplemented by others, sometimes more diagrammatic, illustrating the principal changes that I believe to have occurred during construction and later.[2]

Van Nice's observations, coupled with my own probes in carefully selected positions, leave no doubt that none of the major supporting elements is a continuous homogeneous mass. There are numerous unbonded joins and changes of material as well as far more numerous internal surfaces of weakness in both brickwork and ashlar masonry.[3] And there is extensive cracking throughout, sometimes accompanied by relative rotations or slips of the adjacent masses. This cracking includes separations at joints (both full separations and the splayed ones typically seen in arches), separations due to primary tension failures (around the bases of the dome and semidomes), and splitting of the masonry blocks of the piers under the tensile stresses that inevitably occur at right angles to the primary compression (especially where there are local concentrations of this compression due to uneven bearing between blocks).[4]

It is equally clear that the present structure contains work of many periods, which has undergone different past loadings. Evidence of this is provided by the presence of masonry of markedly different characters, by documentary records of past partial collapses and partial rebuildings, additions, and consolidations, and, less directly, by incompatible deformations.

Structural behavior over the centuries has been affected by all these complexities of construction and changes of form, as well as by the progressive deformation, cracking, and hardening of the large quantities of mortar in the brickwork as construction proceeded above it. The major early shear failures in the walls linking the outer buttress piers to the main piers above the gallery roof are, for instance, of a kind typical of brickwork with very weak mortar.[5]

2 R. J. Mainstone, *Hagia Sophia: Architecture, Structure and Liturgy of Justinian's Great Church* (London, 1988). (Note that in plates A3 and A10 the earlier and later underfloor ties in the west gallery are interchanged: Those in plate A3 should appear in plate A10 and vice versa.)

3 See ibid., plates 106, 120, 132, A2–A10, for the known principal unbonded joins and changes of material.

4 To provide more uniform bearing, lead sheet was inserted in some joints, as it had been, much earlier, in the Parthenon. But it is unlikely that the dressing of the bearing faces of the blocks of the piers was as uniformly precise as in the Parthenon. Some of the resulting splitting may be seen where glass telltales, attached probably in the 1930s, are still in place in the gallery. Similar splitting may often be observed elsewhere in comparable situations. Good examples are found near the feet of the four piers supporting the vault of a deep chamber (cistern?) in the citadel of Aleppo, and more extreme instances, where the splitting may have been due partly to seismic loading, can be seen in ibid., plate 203.

5 Ibid., plates 229, 230, 232.

But now that the mortar has hardened, the adjacent uncracked brickwork has become much closer to what we see in the nearly monolithic fallen masses of other roughly contemporary structures.

Though any modeling, whether to assist in visualization or to permit quantitative analysis, must simplify, it must also, if it is to have any validity, recognize and take into account these changes as far as they are likely to be significant.

Modeling Possibilities

Three basic types of model are available: physical, analytical, and intuitive. A physical model is a smaller physical counterpart of the full-scale structure or of some part of it; an analytical one, a corresponding abstract con t defined essentially by geometry and numbers and mathematical relationships; and an intuitive one, a less precisely defined mental visualization. Attention will be limited in what follows to analytical and intuitive models.[6]

Analytical Models

Static Equilibrium Models

What I here call static equilibrium models explore only the static balance of forces within the structure and external to it, doing so without reference to the elastic deformations always associated with the internal forces. Since the conditions of equilibrium are precise and unvarying, unique precise answers can be expected from them on one condition – namely, that there is only one possible path or set of paths for the loads that are of interest. When there are more possibilities, one will obtain instead a set of answers defining (equally precisely) the limits within which the true answer must lie. For an existing masonry structure these limits can usually be narrowed considerably by taking into account actual observable cracks, slips, and effective articulations at splayed joints.

Static Elastic Models

Elastic models also take into account the relative elastic stiffnesses of different possible load paths and the deformations associated with the internal forces. In this way they are potentially capable of giving unique answers about the forces throughout the structure. But they have a drawback: The answers will be correct only if all the relevant elasticities of the constituent materials, all the relevant internal details of the construction, and all the support conditions

6 See also R. J. Mainstone, "Characteristics and Assessment of Old Masonry Structures", in *Structural Conservation of Stone Masonry* (Rome, 1990), 63–76.

are accurately known and modeled, and if all possible local failures under load and significant inelastic deformations are incorporated into the model.

For masonry structures, these are highly restrictive conditions. Variable elasticities and numerous breaks in continuity resulting from the manner of construction inevitably introduce considerable uncertainties, and the propensity of masonry to crack (without being able to shed loads to adjacent reinforcement) makes far greater demands on modeling techniques than arise in the steel and reinforced concrete structures for which most of these techniques were originally developed.

For all but the simplest structures there can also be considerable computational difficulties, which, for more than half a century, have been overcome by various approximation techniques. Of these, the technique based on finite-element modeling has, over the past two decades and with the huge increase in the number-crunching power of computers, become highly versatile and free of many of the earlier limitations.

In a finite-element model, the structure is notionally decomposed into small elements appropriately connected and given characteristics appropriate to the parts of the structure they represent. Nonlinear behavior – deformations no longer proportional to stress – and cracking can be modeled, subject to certain limitations stemming from the choices of elements, element boundaries, and interconnections.

In relation to masonry structures, it must be remembered chiefly that such finite-element models are primarily models of a real continuum. Thus, they are directly applicable, for instance, to the individual lintel or monolithic slab and to some hardened masses of concrete or brickwork. But they are less directly applicable to the highly heterogeneous masses of most masonry and brickwork, with their numerous discontinuities, relatively weak joints, and often, in dry ashlar masonry, highly uneven bearing between blocks. Successful applications hitherto have recognized this limitation and included the actual discontinuities and joints in the model[7] – something that seems hardly practicable for a complete vast structure like Hagia Sophia.

Dynamic Elastic Models

All dynamic behavior is much more complex than static behavior. The problems of accurate modeling are correspondingly greater. This has meant that attention in the architectural and civil engineering fields has hitherto been restricted largely to the elastic response of certain classes of modern steel and reinforced structures to blast, wind, wave, and earthquake.

For structures such as these, the usual analytical models have assumed linear response and no cracking. Major determinants of this response are the clearly defined modes and corresponding natural frequencies of vibration,

7 See, e.g., the essays in *Structural Conservation of Stone Masonry* by C. Ignatakis et al., R. Barthel, and C. Blasi et al., as well as the following: R. Barthel, "Analysis and Structural Behaviour of Masonry Cross Vaults," in *Structural Repair and Maintenance of Historic Buildings*, ed. C. A. Brebbia, Computational Mechanics Publications (Southampton, 1989), 119–28; and S. Chiostrini, P. Foraboschi, and S. Sorace, "Problems Connected with the Arrangement of a Non-linear Finite Element Method to the Analysis of Masonry Structures," in ibid., 525–34.

which are largely independent of amplitudes. And because of the assumed linear elastic behavior, it is possible to simplify the analysis by considering separately the responses in different modes to the various frequency components of the loading or ground movements and then combining them.

These models are of very limited relevance to the seismic behavior of masonry structures, because the numerous discontinuities and effective articulations mean that behavior at the larger amplitudes that are of real interest is far from being linear elastic.

Dynamic Equilibrium Models

The larger-amplitude behavior of masonry is better represented by the relative rocking motions of articulated rigid blocks in dynamic counterparts of the static equilibrium models considered in a preceding section. It is characteristic of rocking that natural frequencies are not constant with changing amplitude. They decrease markedly as amplitudes increase. So the analysis must follow through the full response, instant by instant, to the actual ground movements.

Some progress has been made, particularly in the past decade, in the realistic analytical modeling of the behavior of both monolithic and multidrum columns, showing inter alia that the response is highly sensitive to the precise sequence of movements and conditions of support, and some confirmatory tests have been made on small physical models.[8] As far as I am aware, there has been no such progress yet in similarly modeling the behavior of even the simplest arched or vaulted structure.

Intuitive Models

Though the unaided human mind is not capable of the same quantitative precision as can be achieved with analytical models, it is infinitely more versatile. Given good three-dimensional powers of visualization – a crucial requirement – and a good understanding of the deformations of materials under load and the conditions of equilibrium, the skilled engineer should be able to form mental models that are both more comprehensive than the ones discussed in the preceding section and less constrained than they are by necessary idealizations, and able to operate on them directly in a truly interactive manner by bringing to bear data from quite different fields.

I have called these models intuitive[9] because they are a form of essentially personal cognition, akin in this respect to the picture that we can build up of another person independently of any attempt we may later make to put it into

8 See, e.g., A. Sinopoli, "Dynamic Evolution by Earthquake Excitation of Multiblock Structures," in *Structural Conservation of Stone Masonry*, 115–22, which includes references to some of the earlier studies. Further tests on physical models have been undertaken recently by Professor G. Manos at the University of Thessaloniki.

9 R. J. Mainstone, "The Springs of Structural Invention," *Journal of the Royal Institute of British Architects* 70 (1963), 57–71. (Revised version: "Intuition and the Springs of Structural Invention," *VIA* 2[1973], 42–63.)

words and going far beyond what we can thus formulate. It is, of course, from such models that the underlying bases of all analytical models originally spring. But the traffic is not just one way. The mental models are, in turn, tested and developed by the insights offered by quantitative analysis,[10] as they should also be by purposeful critical observation and periodic attempts to represent on paper the states of the structure and the modes of behavior that are under consideration.

Static and Dynamic Models

Because the possibilities are so boundless, these models are not so easy to describe. For both static and dynamic modeling, essential ingredients are a clear picture of the stereometry – or three-dimensional geometry – of the structure and of its main constructional details; some picture of the relative stiffnesses of alternative load paths and the effects on these of any cracking and changes over time of the material properties; corresponding pictures of likely load paths and possibilities of failure (the load paths most helpfully, I find, in terms of the trajectories of principal stresses); and (most difficult perhaps) a picture of the overall pattern of compatible deformations.[11] The total picture should also embrace behavior under fluctuating thermal strains and the insidious mechanisms that lead, in any masonry structure, to an inevitable slow growth of certain types of deformation.

Dynamic modeling calls, in addition, for an appreciation of likely inertia loads and the associated rapid movements, both those that are compatible and those that (more hazardously, since they may lead to alternating separations and impacts) may be incompatible. For seismic loading of arched and vaulted masonry structures, it is necessary, moreover, to consider vertical as well as horizontal accelerations, since these can significantly affect horizontal thrusts. Reduced thrusts coincident with out-of-phase movements of supports (such as may easily occur in the later stages of a shock) introduce, for instance, a risk of the irreversible downward slips of the crowns of the arches that are so often observed.[12]

Choice of Model

Though we should, as far as the necessary expenditures are justified, take full advantage of the best techniques available, choices must be made and should be neither indiscriminate nor swayed merely by current fashion. They should take into account (a) the questions that are most relevant to the purpose at

10 See note 9 and R. J. Mainstone, "Stability Concepts from the Renaissance to Today," *Stable–Unstable?* (Leuven, 1988), 65–78.

11 R. J. Mainstone, *Developments in Structural Form* (London, 1975), discusses behavior largely in these terms. See esp. chaps. 2 and 5.

12 R. J. Mainstone, "Typical Structural Forms and Their Seismic Behaviour," *Repair and Strengthening of Historical Monuments and Buildings in Urban Nuclei*, vol. 6 of *Building Construction Under Seismic Conditions in the Balkan Region* (Vienna, 1984), 17–77.

hand, (b) the suitability of the model to the structural form and type of construction, and (c) the accuracy desired.

In the matter of accuracy, it should be remembered that it is always the final accuracy that matters, not just the accuracy of the calculation ignoring errors introduced by necessary idealizations and assumptions. Also, it is better to know what the limits of accuracy are than to have to guess what they are. In this respect at least, static equilibrium models are usually better than models whose final accuracy is highly dependent on inadequately known material properties and boundary conditions and can be assessed only by further analyses to establish the sensitivities to these unknowns.

Making a choice is usually easiest when one is designing a new structure. Nearly all recent research efforts have been devoted to developing models and analytical techniques appropriate to the structures we now build and to the questions of safety and serviceability that they pose. Moreover, strictly correct predictions of behavior may be unnecessary, provided that the predictions place the design firmly within a relevant corpus of proven earlier designs, which is essentially what is achieved by compliance with a modern code of practice. A good designer will, nevertheless, always seek his or her own wider intuitive understanding and be guided partly by this rather than slavishly following a code.[13]

When a structure has been successfully built and survived for a considerable time, its adequacy will, to that extent, be already proven. Its condition and its known past performance will, moreover, be the best evidence of the ways in which it has hitherto borne its loads and of its future capacities. The questions that it poses will thus be concerned more with clarifying what can be observed directly of this performance and perhaps (on this basis) elucidating its history or predicting its future safety. To answer these questions calls for more accurate modeling of the relevant characteristics of the constituent materials and of the precise geometry of the structure, including internal discontinuities.

The first and paramount need, then, is for the fullest possible intuitive model based on close observation of all that the structure can disclose to us about itself in the light of our prior experience, the general insights offered by relevant prior analyses, and all we know from other sources such as any written records. It is *this* model that should guide the choice of appropriate analytical models for quantitative clarification.

Most recent applications of finite-element models to old masonry vaulted structures have totally ignored this fundamental principle. One suspects that, in not a few of them, a major factor has been the seductive attraction of such applications at the present stage of development. Too often, in a search for general understanding, they have been mistakenly seen as alternatives to more realistic and relevant but harder-won intuitive models based on close study of the structure itself.

For the final quantitative analysis of such structures, the serious limitations of all other analytical models strongly favor equilibrium models, with their greater realism and greater and more quantifiable final accuracy.

13 The importance of understanding the structure that is being modeled and how it is likely to behave is stressed further in I. A. MacLeod, *Analytical Modelling of Structural Systems* (Chichester, 1990).

Elucidation of Hagia Sophia's History and Structural Behavior over Time

Previous Studies

Mainstone

My own studies[14] were directed initially to the two closely related objectives of elucidating further the history of the structure and its changing behavior. A second phase included a reconstruction of its sixth-century form as well as considering in more detail the processes of design and construction.

First Phase. At the outset, some of the changes over time were already easily recognized. They included the documented partial reconstructions of the dome and main semidomes, the added peripheral buttressing, and numerous minor fillings of windows and other openings. Some lacks of bond had been observed, and the extensive cracking of the transverse buttress walls above the gallery roofs was visible through the rough plaster rendering of their inner faces. Beyond this, the chief evidences of change and of structural actions over time were the inclinations of most of the vertical elements and corresponding departures from geometric regularity of the principal arches and vaults.

The first phase therefore began with an attempt to elucidate further the three recorded partial collapses of the dome and its supporting arches by drawing on the measurements of these irregularities already available in 1964. The basic hypothesis was that most deviations from an intended verticality of the supporting piers and from intended semicircular profiles of the principal arches and part spherical surfaces of the principal vaults stemmed from deformations during and after construction or from a need to conform to existing adjacent elements that had already been so deformed. This seemed reasonable in the light of an initial intuitive appraisal of the likely structural behavior. Once the significant measures had been identified, numerous further measurements were made to achieve greater accuracy where this seemed necessary.

Partly to validate this approach (and in parallel with studies aimed at dating early attempts to stiffen the connections between the main piers and the answering pierlike staircase towers across the aisles), tests beneath the present surface renderings were next made to confirm another conclusion to which it had led – namely, that there had been an undocumented major reconstruction of the great north and south tympana and of the gallery colonnades beneath them, and that it had been undertaken substantially later than had previously

14 Mainstone, *Hagia Sophia;* idem, "The Structure of the Church of St Sophia, Istanbul," *Transactions of the Newcomen Society* 38, (1965–6), 23–49; idem, "Justinian's Church of St Sophia, Istanbul: Recent Studies of Its Construction and First Partial Reconstruction," *Architectural History* 12 (1969), 39–49; idem, "The Reconstruction of the Tympana of St Sophia at Istanbul," *Dumbarton Oaks Papers,* 23–4 (1969–70), 355–68; idem, "Justinian's Church of Hagia Sophia, later the Mosque of Ayasofya, in Istanbul," *Structural Engineer* 68 (1990), 65–71. (Note that, through editorial errors corrected on p. 101, the scales of figs. 4, 5, 7, and 13 are not as stated in the captions, and the captions of figs. 4 and 7 are interchanged.)

been postulated on the less conclusive evidence of some of the surviving mosaics.[15] This phase of the study concluded with further investigations of the main piers at gallery level and of their buttressing at north and south up to the level of the dome base.

By the time it was completed, the initial intuitive picture of the basic structural behavior and associated progressive deformations was fully vindicated and had been clarified by various other tests (including tests of the mortars and small model tests of the behavior to be expected of the brickwork of the buttressing walls above the gallery roof) and by calculations of some of the major active forces to assess, for instance, the order of elastic deformations and the additional inelastic deformations that must also have occurred at different times.

Among the most important features of this behavior were the following:

1. Total present above-ground deformations of the main supports are between one and two orders of magnitude greater than the present elastic deformations due to gravity loading (those that would now be observed in reverse if gravity could be slowly switched off). This means that, with no significant creep likely in the dry ashlar masonry, relative displacements at cracks, joints, and other discontinuities must have played the major role. The relative deformations up to the gallery level and above it show that differential settlements under the piers (leading to rotations at their feet) must also have played a part, unless there is far more cracking at the lowest levels than seems likely.
2. These deformations increased progressively throughout the life of the structure, though at a diminishing rate, with a large proportion occurring during and soon after construction.
3. The three partial collapses of the dome and its supporting arches and abutting semidomes were primarily collapses of the arches, permitted by outward movements of their springings. Though both the first and second domes contributed to the thrusts that led to these movements, their own partial collapses were the result only of partial deprivation of support at their springing level.
4. Total deformations of the principal arches, semidomes, pendentives, and dome were, like those of their supports, much greater at all critical stages than possible purely elastic deformations. Though plastic yield of the mortar must have contributed here, these elements also must therefore have long been extensively cracked.
5. The three-dimensional conditions of static equilibrium and compatibility of deformations (including displacements at the cracks and at other discontinuities) clearly indicated the general pattern of behavior. In particular they confirmed the initial conclusion about the effects of the different support systems to north and south and to east and west of the dome.
6. The essential feature of this behavior (Figure 93) is that longitudinal thrusts of the dome pass fairly directly through the semidomes and pendentives to the main piers and the secondary piers at the east and west ends, whereas major parts of the transverse thrusts pass only indirectly through the deep broad coupled arches at the north and south, thereby thrusting on the main piers not only transversely but also longitudinally.

15 Mainstone, "Reconstruction of the Tympana."

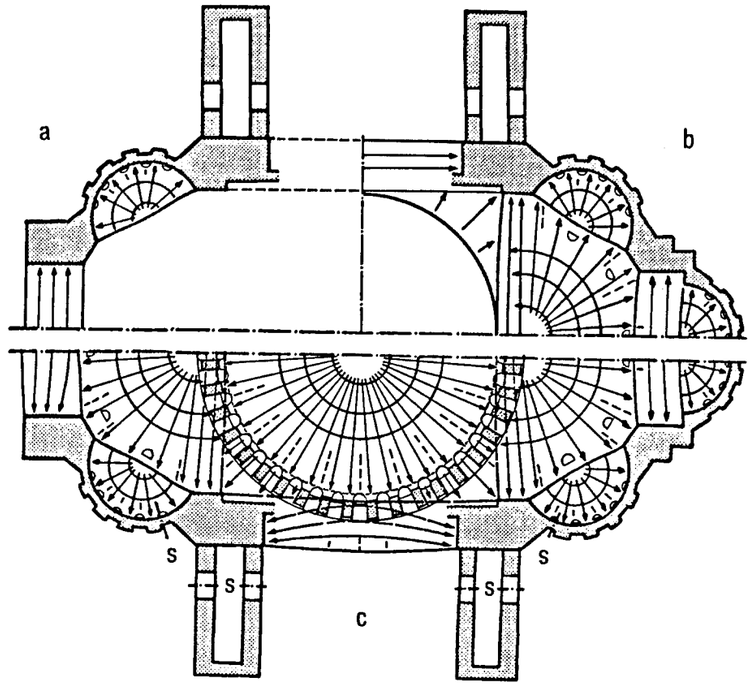

Fig. 93. Thrust lines (arrowed) in the main vaulting system and the general pattern of associated cracking (dashed line) (a) after completion of the small semidomes (assuming that they were completed before the large semidomes); (b) after completion of the large semidomes and pendentives; (c) after completion of the dome. Observation of the cracking has been possible only where it has been exposed by plaster falls or, chiefly at the bases of the exedra semidomes, by deliberate tests. Corroboration of the pattern has been provided, however, by the similar patterns visible in the churches of Hagia Sophia and Hagios Panteleimon in Thessaloniki after the earthquake of 1981.

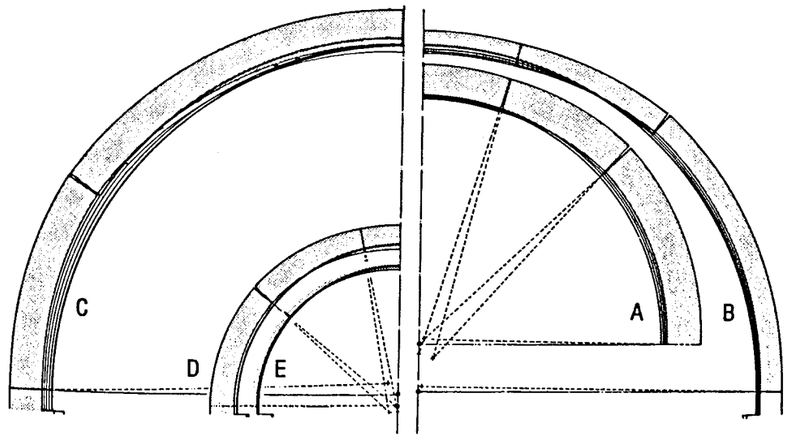

Fig. 94. Successive semiprofiles of most of the principal arches, with the full depths shown only for the present state. (A) Lower main arches at north and south; (B) upper main arches at north and south; (C) main eastern arch with the reconstructed part shown by the dashed lines; (D) bema vault and western barrel vault; (E) forward arch of the apse.

Second Phase. Whereas the first phase concentrated on the levels above the gallery floor where deformations were the greatest and most revealing and where most problems had arisen in the past and most changes had occurred, the following phase paid as much attention to the lower levels to reveal more about the early development of the design and to permit a fuller assessment of the structural behavior.

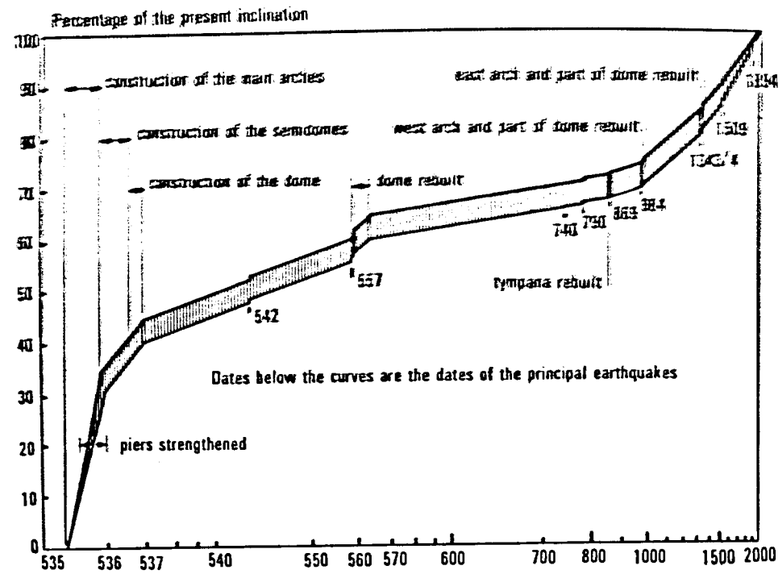

Fig. 95. Average north–south inclinations of the upper stages of the four main piers expressed as percentages of the present average inclination. The width of the band denotes the margin of uncertainty.

This second phase included a more detailed study of the deformations as clues to both the structural behavior and the construction history. Detailed analyses were made of the successive deformations of all but the most minor arches and their supports, as in the examples shown in Figure 94, and the articulations indicated by these analyses made it possible, using precise equilibrium models, to recalculate within narrower limits the principal thrusts that were exerted.

The main conclusions about the sequences of construction and partial reconstruction have already been presented much more fully than is possible here.[16] The following further conclusions about the structural behavior are relevant to any future structural modeling:

1. The growth of the main transverse deformations of the piers was established to within narrow margins up to the present, other critical deformations being deducible from them and from what was established about the sequences of construction and later partial reconstructions. A dimensionless plot of the most revealing measure is reproduced in Figure 95.
2. Though the increases during earthquakes could not be established within the same percent margins of possible error, this was merely because there could be no doubt that they made only small contributions to the present totals.
3. The horizontal thrusts exerted by both first and second domes at cornice level would depend on the extent of radial cracking, but only to a small extent (less than 10 percent) over the possible limits for this cracking. For the first dome they would have been about 50 percent greater than for the second if its profile was as deduced from the surviving evidence and its construction otherwise similar.[17] Its thrusts would have contributed to the outward spread of the piers that allowed the center of the eastern arch to fall, but this contribution would have been relatively small. This dome itself was no more at risk than was its successor while its supports remained intact.
4. Calculations of the outward transmission of the horizontal dome thrusts showed that the indirect way in which the transverse ones reached the main piers led to total longitudinal thrusts on these piers from this source greater than the transverse ones (approximately 2 MN compared with 1.5 MN for the probable first dome and two-thirds of these amounts for the second) in spite of the substantial longitudinal relief provided by the large semidomes and the secondary piers.[18]
5. At a lower level, the additional thrusts on the piers exerted by the main arches as a result of the vertical weight of the dome were, conversely, less longitudinally than transversely (approximately 2 MN compared with 3.5 MN for the probable first dome and slightly more for the second) on account of the considerably smaller spans of the north and south arches. These additional thrusts led to the total thrusts at this lower level being greater transversely, the lesser spans of the north and south arches compensating for their own greater weights.

The attempted reconstruction of the design process will be discussed in a later section.

16 Mainstone, *Hagia Sophia;* idem, "Reconstruction of the Tympana."

Thode

Drawing in part on the conclusions from the first phase of my own study, Thode made further analyses similar to those made in its early stages, leading to broadly similar conclusions about such matters as the relative insignificance of elastic deformations of the piers and the likely significance of differential settlements at their feet.[19] He made no attempt to elucidate further the sequence of construction and subsequent changes or the effects of these on the structural behavior and present structural condition.

Mark and Westagard

In the first published partial finite-element analysis, Mark and Westagard considered only the structural behavior of a hypothetical first dome and its supporting arches, pendentives, and semidomes.[20] Their model was restricted

17 Mainstone, *Hagia Sophia,* plate 237.

18 Ibid., 212. (The relationship between these calculated thrusts was inverted in Robert Mark's review in *American Journal of Archaeology,* 93 [1989], 489–90. Mark apparently failed to distinguish between them and the total thrusts acting at a lower level, as well as misquoting "unforeseen" in a passage on p. 104 as "unseen."

19 D. Thode, "Untersuchungen zur Lastabtragung in Spanantiken Kuppelbauten" (thesis, Darmstadt, 1975), 14–125.

20 R. Mark and A. Westagard, "The First Dome of Hagia Sophia: Myth vs. Technology," in *Domes from Antiquity to the Present,* ed. I. Mungan (Istanbul, 1988), 163–72. (Reprinted without significant change in R. Mark, *Light, Wind, and Structure: The Mystery of the Master Builders* [Cambridge, Mass., 1990], 74–89.)

to one-quarter of this system. Little information was given about it beyond a drawing of the element mesh and the assumptions about support from below – none, for instance, about the elements assumed or the loading. The stereometry was said to be based on the Van Nice survey, but no account seems to have been taken of the very different spans of the transverse and longitudinal supporting arches. Purely elastic support was assumed from only the main and (presumably) the secondary piers, with unspecified elastic properties and cross sections and no rotations of their footings. More important, the window openings in the dome and semidomes were ignored, and uncracked purely elastic behavior was assumed for the whole vaulting system.

Though Mark and Westagard's declared objective was "to learn more about the conceptual design" and the "cause of early pier deformations," such a model could indicate only a potential mode of behavior of a structure broadly similar in form to the actual one but immune from the cracking and major deformations that this experienced from the start. As might be expected, the monolithic behavior and absence of window openings greatly reduced the dome thrusts impinging on the semidomes while the equal spans of all the supporting arches exaggerated the longitudinal thrusts exerted on the piers by those at the north and south. To claim that this analysis suggested further revision of our understanding of the Hagia Sophia's structure was therefore unwarranted. On the contrary, I see it as demonstrating the crucial importance of correct modeling if valid answers are to be obtained.

Hidaka, Aoki, and Kato

Hidaka, Aoki, and Kato less ambitiously restricted their attention to representative cross sections of the first and second domes.[21] Their models were also finite-element ones and were much more adequately described. The cross sections were taken from my work,[22] and the models included elastoplastic joint elements in the planes of the sections, so that cracking in these planes could be (albeit somewhat arbitrarily) taken into account, as could cracking normal to them, though hoop stresses were apparently allowed even where continuity was interrupted by windows. Once again, purely elastic behavior was considered, with elasticities and strengths arbitrarily chosen within the wide ranges possible. Rather than a direct modeling of the supports, the restraint they gave to the dome's horizontal thrusts was included as a variable multiple of that given by an arbitrarily assumed circumferential tie at the base. No rotation appears to have been allowed at the base of either dome.

Within its narrow limits, this analysis was open to criticism chiefly on account of the way in which crack formation and modes of deformation were limited by the placing and inclination of the joint elements and some of the other assumptions just referred to. Those limits are open to more serious criticism, however.

The declared objective was now to clarify the "structural superiority" of the second dome. Since both statical analysis and the recorded survival of the first dome in 558, unharmed except for that part of it that had been deprived

21 K. Hidaka, T. Aoki, and S. Kato, "Structural Stability and Profile in the Dome of Hagia Sophia, Istanbul," in *Structural Repair and Maintenance*, 267–76.

22 Mainstone, *Hagia Sophia*, plates 237, 240.

of support from below,[23] show that it was adequately stable in itself, the true structural superiority of its successor could lie only in its reduced thrusts on the supports. Given the extent of spreading at the base, the consequent cracking, and the interruptions of circumferential continuity by the windows, these were better determined (within calculable close limits as above) from appropriate equilibrium models.

Outstanding Questions

Since my own studies focused on the form and structure of the sixth-century church and considered its structural behavior only in so far as this threw light on the design problems, construction sequence, and the problems encountered during construction and in the early years afterward, some aspects of the full history and behavior received much less attention.

Most relevant to a wider structural study are the precise chronology of the added peripheral buttresses, the construction of some of them (are they solid or not, and does the one at the southeast incorporate an earlier ramp like that at the northeast?), and their structural roles. Also relevant are some details of the internal construction of the piers, pendentives, and dome base (the last certainly never a single solid mass and originally less solid than now), and of the superimposed pairs of main arches at north and south, and the influence of these details on the overall behavior.

My quantitative analyses were, moreover, restricted to static conditions. Partly because the analysis of the growth of the major deformations showed that dynamic earthquake loadings resulted only in relatively small increases, such loadings were not considered further.

Suitable finite-element models could play a limited role in relation to some of these topics, chiefly in elucidating the possible contributions to total deformations of plastic yield of the mortar and creep of the foundations. But since the main aspects of the overall behavior are qualitatively fairly clear, and adequate data on yield and creep characteristics are lacking, the returns are unlikely to be commensurate with the effort called for or to add to our historical understanding.

Current Princeton Studies and Proposals

The current Princeton modeling proposals[24] seem to be directed solely to further analysis of the structural behavior, but throughout the building's history rather than just at the outset. The impossibility of establishing directly the relevant material properties is acknowledged, and what is already known of this history is taken as an alternative starting point, thereby logically precluding any further elucidation. In practice – though reference is made to "historically documented deformations" – this means accepting my own

23 Paulus Silentarius, *Descriptio ecclesiae sanctae Sophiae*, ll. 186–204, in *Patrologia Graeca*, 86, and in a revised edition with German translation, P. Friedlander, *Johannes von Gaza und Paulus Silentarius* (Leipzig, 1912).

24 Robert Mark, Ahmet Ş. Çakmak, and Mustafa Erdik, "Preliminary Report on an Integrated Study of the Structure of Hagia Sophia: Past Present and Future," this volume.

conclusions about their development and about the construction sequence and successive changes in form.

The chief objective has been stated as the construction and calibration of an accurate numerical model to reproduce both past and present structural behavior, dynamic as well as static and including structural failures. What is proposed must be assessed accordingly.

The model is to be limited to what I identified as the primary structural system (Figure 96). Calibration to determine the properties of the constituent materials is to be undertaken by repeated inverse analyses, comparing predicted with known failures, predicted with known present and past deformations, and predicted present dynamic response with observed low-amplitude vibrations of the structure itself. Doubts arise on the following scores:

1. In restricting the model to this "primary system," two things seem to have been overlooked. First, because my purpose was different, the foundations were ignored. They cannot be ignored for the present purpose. Second, I included as "supplementary elements" the buttresses added later outside the main rectangle. They also cannot be ignored in the later periods.
2. Though the significance of cracks and separations is acknowledged, there seems to be no intention to choose the element meshes in such a way as to permit the direct modeling of the crack development or even to model all the principal lacks of bond. Nor is there any reference to the prior intuitive modeling that this would call for where it is impossible to observe even the present cracks fully. The intention seems, rather, to recognize the effects of the cracking and at least some of the other discontinuities "macroscopically" by assigning suitable properties to elements that are themselves cracked or separated by unbonded joints.
3. Even for the quasi-static behavior of such models, the time-consuming calibration procedure proposed to establish these properties cannot lead to unique results where the overall behavior indicated by the assumed deformations is statically indeterminate. It cannot, for instance, indicate how transverse thrusts are shared between the main and buttress piers. Nor can it distinguish between plastic flow in the mortar and slips or separations as causes of nonelastic deformations, though these will have different effects on future behavior. It will merely lead to changing properties over time that reflect the combined effects of yield, mortar hardening, and cracking – a poor basis for assessing future behavior.
4. The proposed final tuning for elastic dynamic performance is likely to present problems at least as great and, though relevant to the loads that would now be experienced initially in a possible earthquake, will be far less relevant to the larger-amplitude responses on which the safety of the monument will depend. Valid dynamic modeling of these larger-amplitude responses is possible only if the actual cracks and other discontinuities that give rise to articulations and permit separations are directly represented in the model.

More generally, the choice of a modeling technique that is ideally suited to the study of an elastic continuum to study, without any prior and more comprehensive intuitive modeling, a structure in which cracking and other discontinuities created, almost from the onset, numerous real discrete elements

AA, CC main arches
BB upper north and south arches
DD east and west barrel vaults
EE exedrae semidome arches
FF exedrae semidomes (cut away at the top)
G main eastern semidome (western counterpart cut away to show better the structure behind)
HHH pendentives (western ones cut away to show structure behind)
aaaa pier projections (see text)

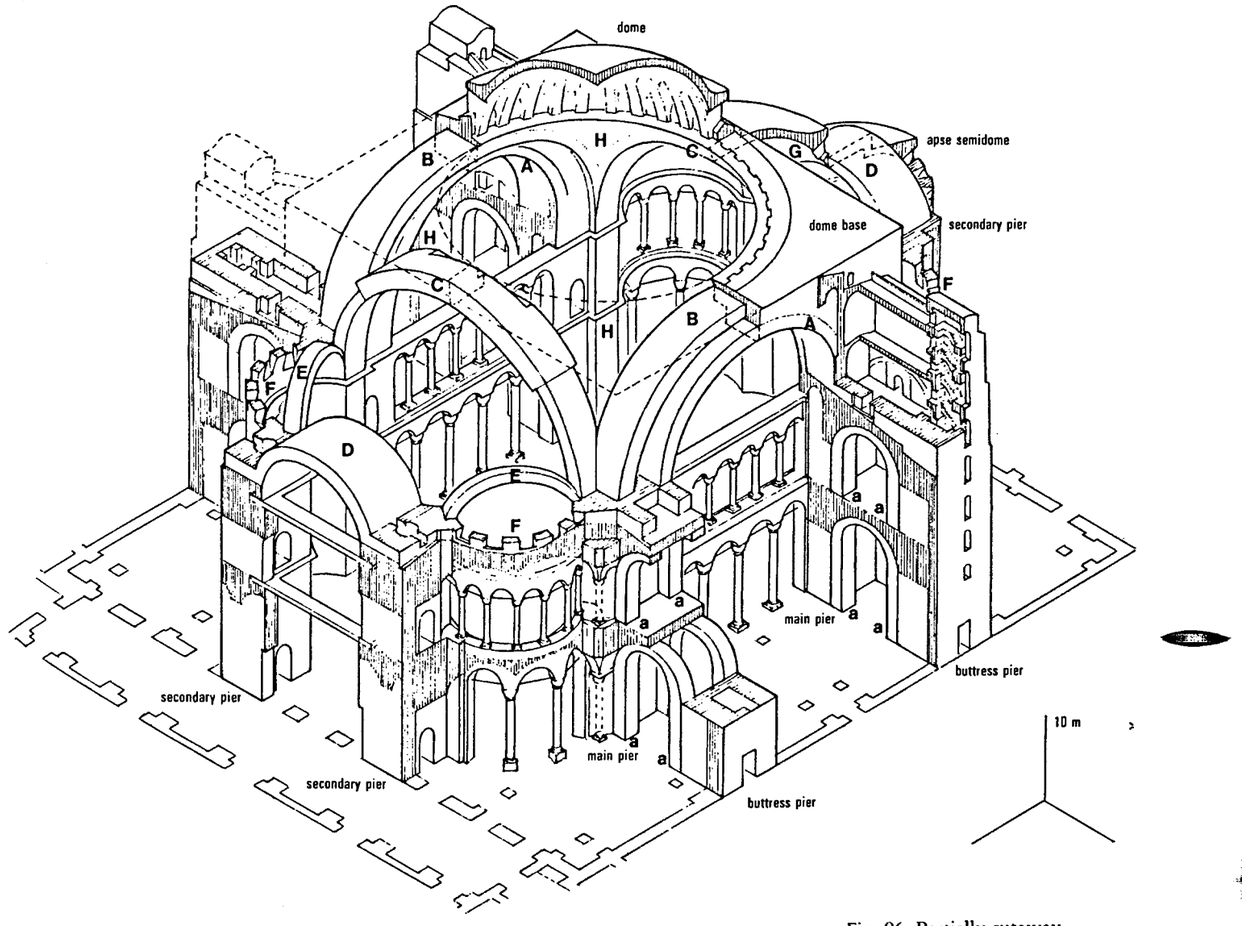

Fig. 96. Partially cutaway isometric of the primary structural system (see also note 2).

calls for vastly increased computation for what seems to me an illusory gain. It leaves the impression that the real objective was to test this technique against a new challenge. Again, it must be said that, however laudable it may be to use to the full the resources of modern theory and computational techniques, this should not be misconstrued as using whatever is newest or of greatest current interest irrespective of its suitability for the task at hand.

Justinian's church is a unique structure of immense interest and value. Should we not really be asking how the outstanding questions can best be answered, recognizing that, with our incomplete knowledge of even the present fabric and very inadequate documentation, definitive answers to some are impossible to obtain today and may well continue to elude us?

Elucidation of the Sixth-Century Design Process

Questions about design, I believe, can be tackled only on the dual bases of the limited direct (documentary) evidence we have and what can be firmly deduced from a much wider range of evidence about what was actually done when the church was designed, set out, and built. Though Anthemius and Isidorus were masters of the science of their day, they were far from able to perform structural calculations of the kinds that have become possible in recent centuries. The bases of their design must be sought elsewhere.

My own approach was to start, on the one hand, from what was known or could be found out about the whole relevant background and, on the other hand, from the surviving evidence of what was actually done. Thanks to a unique accuracy in setting out and an equally unique disposition of the principal supporting elements, much can be learned about early overall intentions from the ground plan alone. Further studies of the precise sequence of construction then clarified the role of the empiricism that is characteristic of all early innovative design.[25]

Even if we had a perfect structural model and knew everything about its behavior, I do not think that we could logically deduce from it anything further about design objectives and procedures. The contrary belief that is implicit in some recent inferences about designers' approaches in the past stems from the fallacy that what we find significant in this behavior can be equated with what they also found significant, foresaw, and intended, and from too narrow a view of the problems that they confronted.[26]

Structural Safety

Structural safety is a very different matter. History has its value and its uses, which I have discussed elsewhere.[27] But wrong, incomplete, or unhelpful interpretations can be improved upon, causing no lasting harm. Failure to act

25 Mainstone, *Hagia Sophia*, chaps. 7 and 8; idem, "Structural Theory and Design before 1742," *Architectural Review* 143 (1968), 303–10.

26 A further discussion of this will be one topic of a forthcoming paper on structural analysis and historical interpretation.

27 R. J. Mainstone, "The Uses of History," *Architectural Science Review* 20, (1977), 30–4.

wisely in caring for one of the greatest works of architecture of all time could be irreparable.

Current approaches to the structural conservation of historic masonry structures often leave much to be desired. Increased concern in recent years has led to advice being sought from many engineers who, though highly skilled in the design of modern structures, are ignorant of the peculiarities and needs of vaulted masonry. In the absence of directly applicable agreed-upon and codified procedures, such engineers tend to see the structure entrusted to them as a poor counterpart of what they would design today, failing to recognize its real strengths and weaknesses. They analyze it as if it had been built in a way with which they are familiar and then reinforce it to conform more closely to the assumptions of their analysis, often shortening its life thereby.

The situation is changing, however. The fact that analyzing the safety of an existing structure calls for a different approach and a different type of model than does designing a new one is being more widely recognized. So are the shortcomings of elastic approaches and the greater relevance to masonry structures of approaches based primarily on equilibrium alone.[28]

If an equilibrium approach is usually to be preferred for the assessment of safety under static loading, it is a fortiori called for where there is a seismic risk, for the reasons already noted. Yet as also noted, proven suitable models do not yet exist. There is a major need for the development of such models, though I think that it should focus initially on far simpler structural systems than that of Hagia Sophia. In principle, finite-element models could play a part, but only if they are able to reproduce adequately the articulations that develop as amplitudes increase and such other phenomena as damping, buffeting arising from out-of-phase movements, and irreversible slips. Until adequate dynamic models are developed, quasi-static analyses, with all their imperfections, still seem to be the best quantitative guide for simpler structures from late Roman domed rotundas to the typical later domed Byzantine church.[29]

Yet for Hagia Sophia, meaningful analyses, even of this kind, are more difficult on account of uncertainties about the condition of much of the masonry. If, in view of these uncertainties, precautionary interventions (beyond a highly desirable and sometimes neglected normal maintenance) are deemed advisable, the aim should be to ensure that the lateral thrusts are adequately

28 See, e.g., *Structural Conservation of Stone Masonry;* also Mainstone, "Stability Concepts from the Renaissance to Today." The most vocal recent advocate of such an approach has been Jacques Heyman, writing in a long series of articles beginning with "The Stone Skeleton," *International Journal of Solids and Structures* 2 (1966), 249–79. See, more recently, idem, "The Care of Masonry Buildings: The Engineer's Contribution," in *Structural Repair and Maintenance*, 3–12; and "Poleni's Problem," *Proceedings of the Institution of Civil Engineers* 84 (1988), 737–59. His insistence on adopting a "plastic" limit-state approach based on assumptions that exclude failures induced by local high stresses and ignore the effects of large inelastic deformations is, however, regrettable, because the substitution of idealized for true limits calls for a "geometric" factor of safety that will often be much larger than it need be. See, in this connection, my unanswered comments in, e.g., the discussion on "Poleni's Problem," ibid., 86 (1989), 549–51.

29 *Repair and Strengthening of Historical Monuments and Buildings in Urban Nuclei*, 94–5, and 191–4; K. Stylianidis and C. Ignatakis, "The Importance of Phase-by-Phase Limit Analysis of a Monument," in *Structural Repair and Maintenance of Historic Buildings*, 569–79; idem, "The Analysis of a Byzantine Monument," in *Structural Conservation of Stone Masonry*, 131–8; and George Penelis, Maria Karaveziroglou, Kosmos Stylianidis, and Demetrios Leontaridis, "The Rotunda of Thessaloniki: Seismic Behavior of Roman and Byzantine Structures," this volume.

contained and to limit potentially damaging seismic responses such as out-of-phase movements of supports. These should be done without sacrificing the beneficial characteristics of the present overall response of the building and with due respect for its integrity and character. It would also be good if, before any major work was embarked upon, it were the subject of international consultations similar to those that have taken place in recent years to guide the exemplary current work on the Parthenon.[30]

30 *Proceedings of the 2nd and 3rd International Meetings for the Restoration of the Acropolis Monuments*, Committee for the Preservation of the Acropolis Monuments (Athens, 1985, 1990), and the (preparatory) *Studies for the Restoration of the Parthenon*, Committee for the Preservation of the Acropolis Monuments (Athens, 1983, 1988).

THE OTTOMAN HAGIA SOPHIA AND RELATED BUILDINGS

STRUCTURAL INFLUENCE OF HAGIA SOPHIA ON OTTOMAN MOSQUE ARCHITECTURE

METIN AHUNBAY AND ZEYNEP AHUNBAY

Ey cümle-i camilere sultan Ayasofya
Vey Kâbe sı fat cemile bercan Ayasofya
Lâtifi,[1] 983 H./1575

Encountering Hagia Sophia

There is no doubt that Hagia Sophia made a deep impression on Ottoman architects and inspired them in their work. Its imposing size gave rise to legends about its design and construction.[2] Among Ottoman writers of the sixteenth and seventeenth centuries there is the common opinion that it could hardly be surpassed. Even after the construction of imperial mosques like Fatih and Süleymaniye, Hagia Sophia kept its established position in the Ottoman capital.[3]

The Ottomans had great respect for Hagia Sophia and did their best to keep it standing. The decree of Selim II silencing the opposing opinions about the demolition of the accretions to the structure reveals the two aspects of its conservation: as a mosque and as a historic monument.[4] While the Ottoman architects inspected and reinforced its structure, they gained more insight into its construction and fabric. Though we do not know the extent of the work, Hagia Sophia's structure was reinforced with additional buttresses around the year 1573.[5] As Sinan, the celebrated Ottoman architect of the sixteenth century, was supervising this restoration, he probably had a chance to inspect its

1 *Evsâf-ı Istanbul*, ed. N. Sunar Pekin (Istanbul, 1977), 84; original manuscript dated 1524, revised 1575.
2 Ibid., 81; Evliya Çelebi, *Evliya Çelebi Seyahatnamesi*, ed. Z. Danışman (Istanbul, 1969), 1: 62, 64, 128–40.
3 Lâtifi, *Evsâf-ı Istanbul*, 28; *Evliya Çelebi Seyahatnamesi*, ed. Danişman, 128.
4 Ahmet Refik, *Onaltıncı Asırda Istanbul Hayatı (1553–1591)* (Istanbul, 1935), 22–4.
5 Ibid.

structure more carefully. In *Tezkiret ül-Bünyan*[6] and *Tezkiret ül-Ebniye*,[7] written by the poet Mustafa Sâî Çelebi, Sinan relates his annoyance at discussions concerning the absence of a great domed structure like Hagia Sophia in Islamic architecture. This is important, because Christian architects of the time boasted about it and claimed to be superior to Muslims. Announcing that it was very difficult to sustain a dome of such size, they concluded that, if the Muslims could, they would certainly build one in recompense. Sinan states that this argument was a source of sorrow for him; so while building the Selimiye in Edirne, he intended to surpass Hagia Sophia by constructing a wider and higher dome.[8]

Sinan's words can be interpreted as a clue to the fact that Hagia Sophia's supreme presence acted as an impetus for Ottoman architects. It inspired them to build wider and higher domes. The emphasis was on the size of the dome; the structural scheme was a secondary item. Nevertheless, it is apparent from the outstanding monuments of the period that both aspects of this theme were present.

The essence of Hagia Sophia's structural scheme, a dome suspended on four arches and pendentives, had been one of the common themes of the ancient world. The structural integration of the dome with two semidomes of the same diameter, however, was not very common. With Hagia Sophia, it became universally known and appreciated, but it did not find a powerful echo in Late Byzantine architecture. Up to the fifteenth century, the Ottomans followed a different line of development with their major domed structures: It consisted mainly of exercises with multipurpose mosques having a central domed bay encircled by other cellules, as well as with single-domed prayer houses. The structural composition created by a central dome with two semidomes was quite exceptional for these architects. After they gained direct access to the revolutionary structure of Hagia Sophia, major changes took place in their design of Ottoman mosques.

Reflections of Hagia Sophia's Design

In the development of the Ottoman mosque in the first half of the fifteenth century, there was a striking tendency to integrate monumental domes into the structure, as manifested in the Üç Şerefeli Mosque of Edirne. The architectural climate after the conquest of Constantinople marked a turning point in the Ottoman classical period. The imperial mosque of Mehmed II in Istanbul (1463–70) had a structural scheme that incorporated some new ideas for the Ottomans. It had a central dome with a single semidome of the same diameter in the qibla (southern) direction. The main dome was suspended on four arches, which were supported by two engaged and two free-standing piers. As such, it may be considered a step back from Hagia Sophia's structural scheme, though its relation to the multipurpose *"futuwwa"* mosques of earlier Ottoman architecture is quite distinct. Yet the fifteenth-century Ottoman historian Tursun Beg asserts that its design is similar to that of Hagia Sophia.[9]

6 S. Saatçi, *Mimar Sinan ve Tezkiret ül-Bünyan*, ed. M. Sözen (Istanbul, 1989), 114, 170–1.
7 R. M. Meriç, *Mimar Sinan, Hayatı, Eseri I* (Ankara, 1965), 61.
8 According to Sinan, Selimiye's dome is six ziras (approx. 4.5 m) higher and 4 ziras (approx. 3 m) larger in circumference.

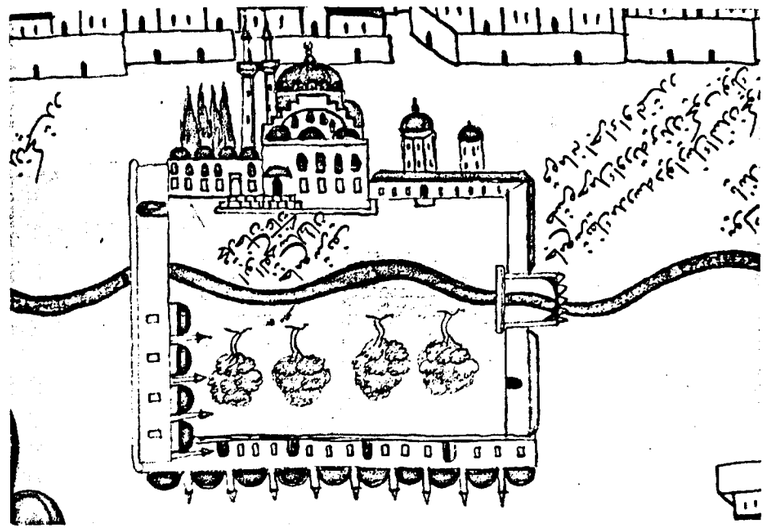

Fig. 97. Mosque of Fatih Mehmet II.

The mosque of Fatih was a daring venture for Ottoman architecture. The suspension of its central dome on four arches and the introduction of a semidome in the qibla direction were important contributions to the development of the Ottoman mosques. It paved the way for the imperial mosques that employ structural schemes similar to that of Hagia Sophia. The central dome of this mosque collapsed in the earthquake of 1766 and consequently was reerected with a new structural scheme. We learn about the original design from descriptions and drawings (Figure 97). Its smaller followers, which are still in existence and provide material evidence of its design, are the mosques of Rum Mehmet Paşa (1469) and Atik Ali Paşa (1497) in Istanbul and the mosques of Selimiye (sixteenth century) and Şerafettin (1636) in Konya.

Though its dome is much smaller (only 16.78 m at gallery level), the central dome of the mosque of Bayezıt II (1505), the second imperial mosque in Istanbul, is flanked by two semidomes nearer to the structural scheme of Hagia Sophia.[10] But it can be regarded only as a simplified version of its grand model; the details are far less elegant, the piers and buttresses are much smaller, and there are no exedrae or side galleries.[11] Yet this mosque has a rational structure that is crucial for its stability. Even so, it was damaged by earthquakes in 1509 and 1766; the present structure embodies sixteenth- and eighteenth-century repairs and consolidations (Figure 98).

The Süleymaniye and Kılıç Ali Paşa mosques in Istanbul are also monuments that have essentially the same structural conception as Hagia Sophia. Among the three sixteenth-century mosques that exhibit structural traits sim-

9 *Tarih-i Ebu'l Feth*, ed. M. Tulum (Istanbul, 1977), 70.
10 A. Yüksel, *Osmanlı Mimarisinde II. Bayezıd, Yavuz Selim Devri (1481–1520)* (Istanbul, 1983), 5: 193.
11 G. Goodwin, *A History of Ottoman Architecture* (London, 1971), 169.

ilar to those of Hagia Sophia, Kılıç Ali Paşa Mosque (1580–1) is the one that most resembles it (Figure 99). As Evliya Çelebi noted in his *Travels,* "it is built exactly in the style of the great Hagia Sophia."[12] In addition to the adoption of Hagia Sophia's major structural scheme, the interior space has basilican features that are strikingly alien to an Ottoman mosque.

As can be seen from the construction dates of the mosques employing the structural conception of Hagia Sophia, it continued to be a model for Ottoman architects until the seventeenth century. Besides the mosques with two semidomes, Ottoman architects have employed structures with three and four semidomes. Some of these are the Fatih Paşa in Diyarbakır (1522); the Lala Mustafa Paşa in Erzurum (1562–3); the Mihrimah Sultan (1547–8) and Şehzade mosques (1578) in Istanbul; Yeni Cami (1597–1603; 1661–4); Sultan Ahmet (1617); the second Fatih Mosque (1771) in Istanbul; and the Mehmet Ali Paşa Mosque (1848) in Cairo. Not all of these can be regarded as direct descendants of Hagia Sophia; however, the prime constituents of such structures, the main dome and semidomes, make sometimes remote, sometimes direct, references to Hagia Sophia.

Themes Adopted from Hagia Sophia

Apart from the reevaluation of its basic structural pattern, there are themes in the Ottoman structural vocabulary that are adopted from Hagia Sophia. These manifest themselves in such constituent elements of the mosques as the dome, semidomes, main arches, piers, buttresses, and galleries.

The Dome

In Ottoman architecture, the sizes of the domes ranged between 10 and 20 m, until the beginning of the fifteenth century. Yıldırım Mosque from 1382 in Mudurnu had a single dome whose span was about 20 m. With the Üç Şerefeli Mosque in Edirne, the climax of the preconquest period was reached. Here the centrally organized space has an area 27 m wide and 24 m deep under a dome on six supports. The dome base itself has a diameter of 24.80 m. Thus, a tendency for domes of wider spans is apparent in fifteenth-century Ottoman architecture just before the conquest of Constantinople.

The first imperial mosque in Istanbul, Fatih, had the largest span (26 m) that Ottomans had attained with the four-support system before Sinan. Though this monument does not exist today, Ayverdi has worked out its dimensions quite accurately with the help of remaining original fabric and historic documents.[13] Even after almost seventy-five years, Süleymaniye (1550–7) did not exceed the span of the Fatih Mosque; its central dome measures approximately the same size.

Early Ottoman domes are brick hemispherical shells with a thick masonry belt at their bases. This drum or pseudodrum creates a very austere, solid look that is typical up to the mid-fifteenth century. In general, the belt is

12 *Evliya Çelebi Seyahatnamesi,* ed. Danışman, 2: 140.
13 E. H. Ayverdi, *Osmanlı Mimarisinde Fatih Devri (1451–1481)* (Istanbul, 1973), 3: 363–75.

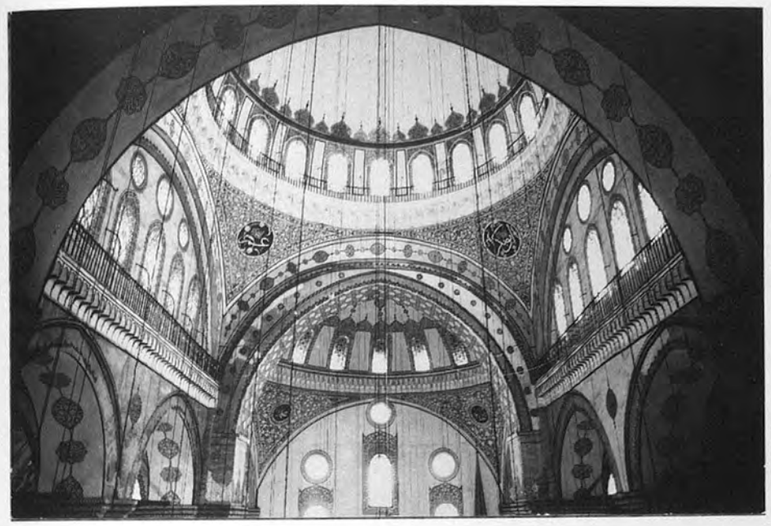

Fig. 98. Mosque of Bayezıt II.

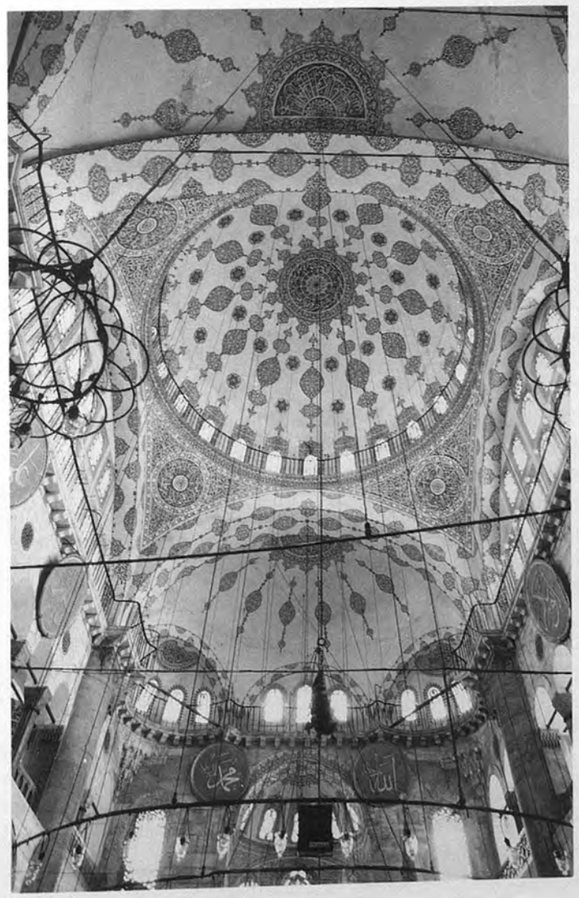

Fig. 99. Mosque of Kılıç Ali Paşa.

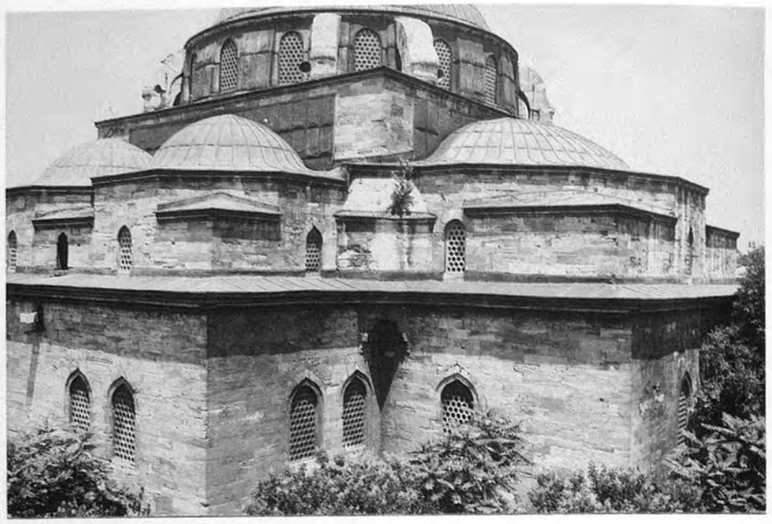

Fig. 100. Mosque of Atik Ali Paşa.

polygonal on the exterior; it can also be cylindrical. Drums were usually pierced with four openings on the cardinal axes of a dome or with eight openings if the belt was octagonal. The thickness is 1.5 m in Üç Şerefeli; the height of its belt, estimated from the dome base in the interior, is 4.5 m. Ottoman mosques started to have more windows on the drums of their domes in the second half of the fifteenth century. The closely spaced windows of Hagia Sophia's dome must have generated great fascination; the technique was used immediately thereafter in the Fatih Mosque. However, lesser monuments in Istanbul contemporary with this mosque conformed to the archaic type. It is interesting that their domes preserved the thick belt with little fenestration, whereas Atik Ali Paşa, a smaller derivative of the Fatih Mosque, adopted the new mode of dome construction (Figure 100). The dome belt contained a ring of window openings, as in Hagia Sophia; the base was reinforced by a row of short buttresses. In the interior, a gallery over the dome cornice, another detail modeled after Hagia Sophia, was introduced (Figure 101). Relying on Evliya's reference to two levels of galleries for the oil lamps in his description of the Fatih Mosque, it may be assumed that this mosque was probably the first to have a path for the lamplighters.[14] Such a feature was not used in the Rum Mehmet Paşa Mosque at Üsküdar.

Semidomes

The Ottomans adopted the structural integration of the main dome with one or more semidomes of the same diameter after the mid-fifteenth century. Although earlier mosques incorporated central domes with a semidome of smaller size in the qibla direction, these did not pose structural problems aris-

14 *Evliya Çelebi Seyahatnamesi*, ed. Damışman, 1: 142.

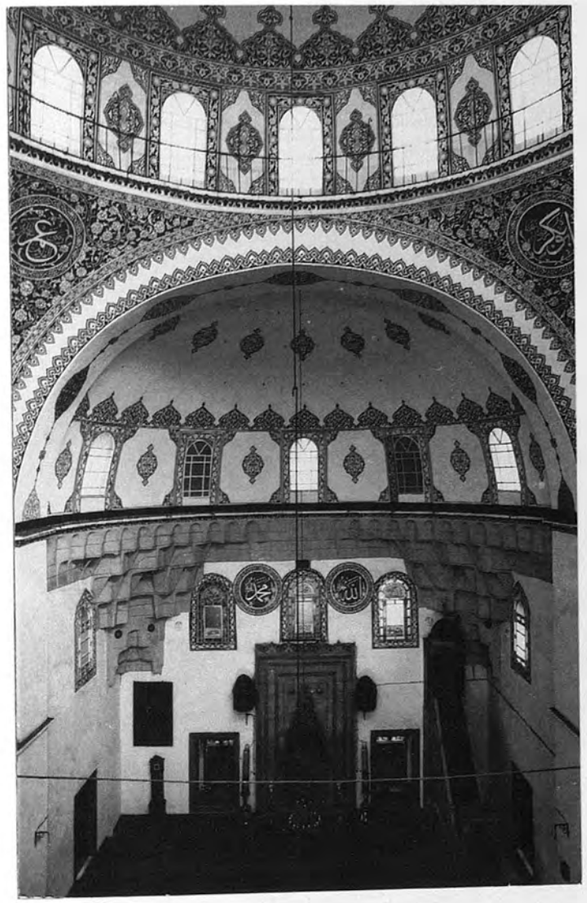

Fig. 101. Mosque of Atik Ali Paşa.

ing from this specific combination. In Hagia Sophia, the supporting arches of the main dome are at the same time the crown arches of the semidomes; in fact, the main arches are merely indicated. This is not true of Ottoman structures in general; semidomes do not abut against the main arches at their intrados but are recessed, leaving the strong main arches as separate bodies (Figure 102). A tendency toward solid and safe construction must have led to this change. Where it was possible to investigate the fabric, as in the Şehzade and Sultan Ahmet mosques, the main arches proved to be constructed of ashlar, which lent them further security.

Transition Level

In early Ottoman architecture, generally, the transition level comprised squinches or a belt of triangular prisms. The use of pendentives was mainly confined to less conspicuous parts of the structure. With the debut of large-

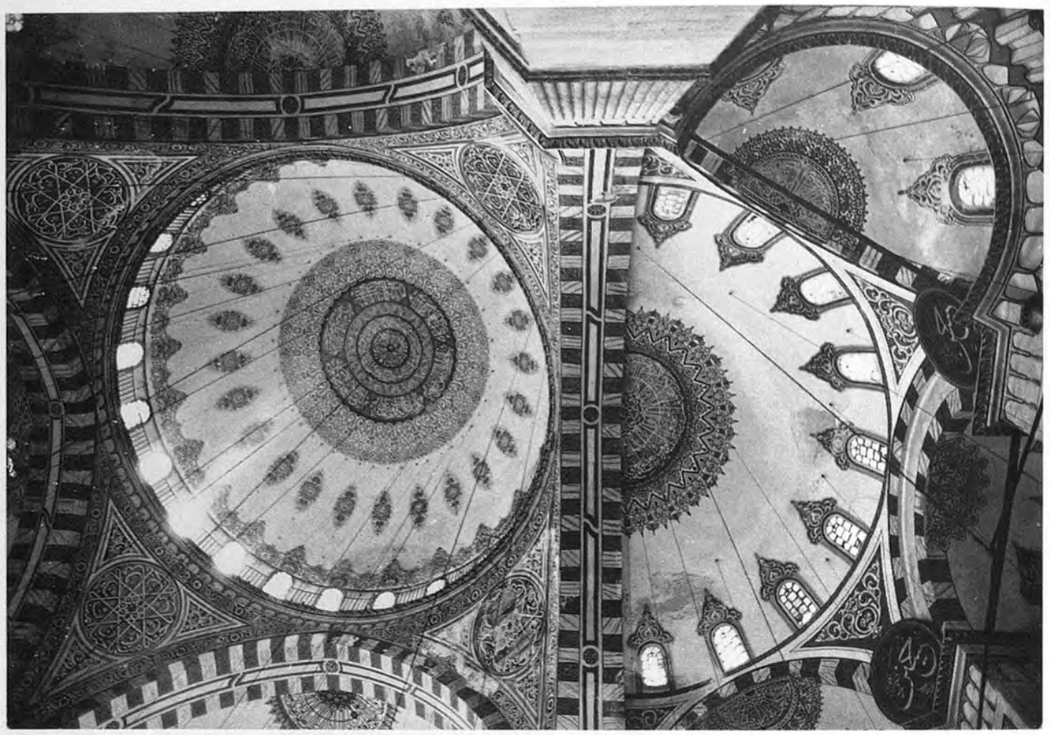

Fig. 102. Sehzade Mosque.

span domes over squares in the imperial mosques in Istanbul, pendentives attained an established position under the main dome. Following the model of Hagia Sophia, the squinches were subordinated to the pendentives and were reserved as transition elements under the semidomes.

With the introduction of pendentives under the main dome, a cubic body was formed over the haunches of supporting arches that enveloped the pendentives, recalling Hagia Sophia. After the practice of employing pendentives under the main dome was established, an attempt to break the solid geometry or the cubic character of this dome base took place. This was accomplished by Sinan in such mosques as Süleymaniye (Figure 103) and Mihrimah Sultan at Edirnekapı, where the spherical outer surfaces of these structural components are emphasized.

Main Arches

In early Ottoman mosques, the supporting arches of the domes were concealed externally behind solid masonry. A probable influence of the exposed lateral main arches of Hagia Sophia on postconquest mosque elevations can be detected as early as the Fatih Mosque: In the Köprülü Water Conveyance

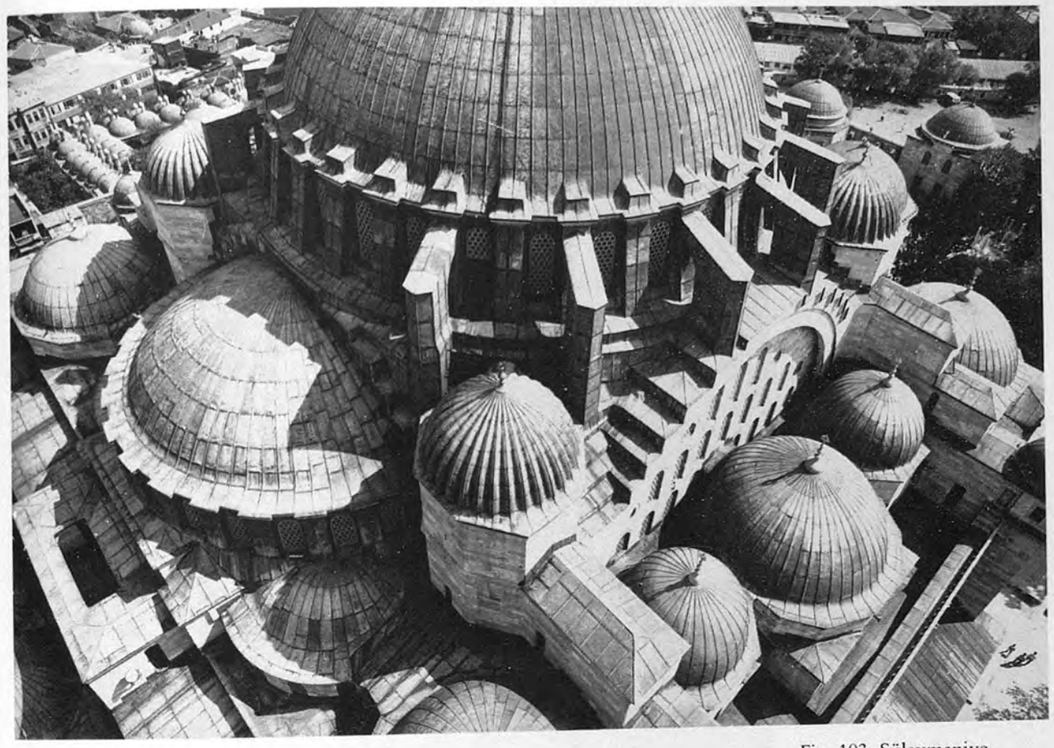

Fig. 103. Süleymaniye Mosque.

Map from the second half of the seventeenth century, this feature is visible on the lateral side (Figure 97).[15] The representation of the entrance facade of the same mosque in Matrakî's drawing of 1534 suggests a protruding sustaining arch on the third side.[16] But this is not yet an established practice, and it may rather be compared to the arch in an early mosque of Sinan, the Mihrimah Sultan at Üsküdar (Figure 104), where a curved delineation without voussoirs simulates a sustaining arch on the northwest wall. In fact, this is just a reflection of the interior structural arch on this side; likewise, Fatih's entrance elevation could be simulating an arch.

In the mosque of Bayezıt II, the lateral supporting arches are semicircular as in Hagia Sophia (Figure 105); later the pointed arches of Süleymaniye and Kılıç Ali Paşa revert back to the pointed arch of Ottoman tradition. The asymmetry of Hagia Sophia's structure resulted in greater widths of the main arches on the northern and southern sides. Lesser spans, voussoir arches, and rational dome curves in Bayezıt II and Süleymaniye made extraordinary arch widths uncalled for. Nonetheless, the main piers of Süleymaniye have wider faces on the north–south axis than on the east–west axis; respectively, the lateral main arches are wider than those on the main axis.

15 Köprülü Library, Istanbul. 16 Istanbul University Library, MS no. 35.

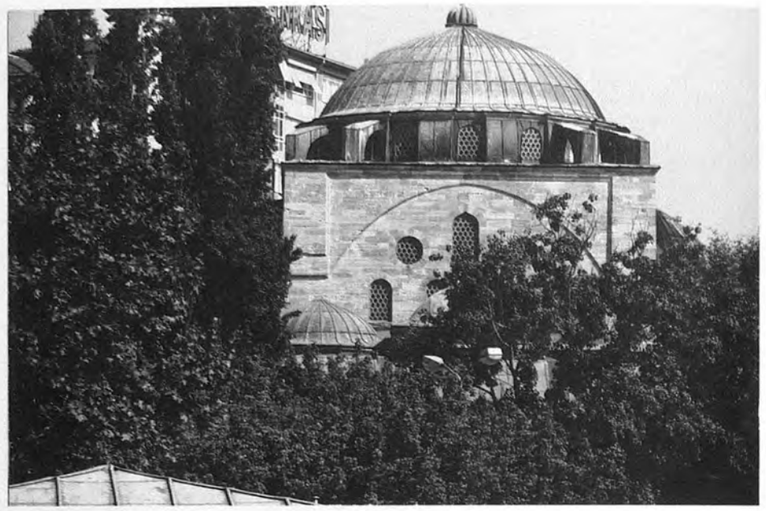

Fig. 104. Mosque of Mihrimah at Usküdar.

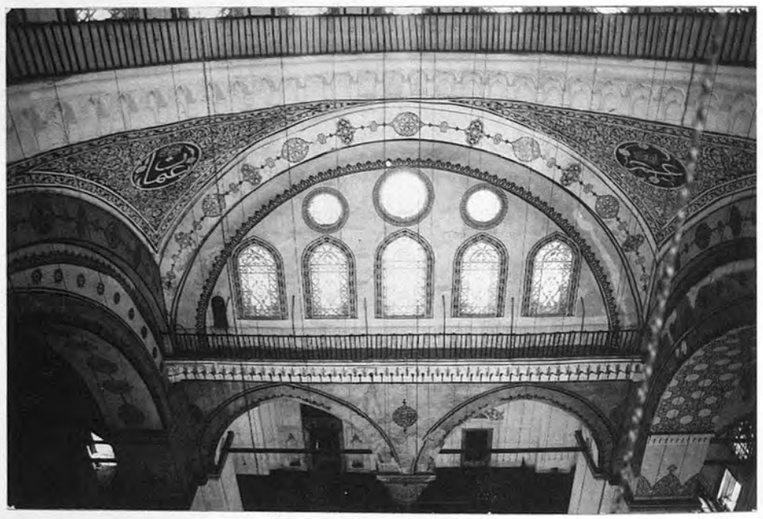

Fig. 105. Mosque of Bayezıt II.

Piers

As a result of the frequent recurrence in the fifteenth through sixteenth centuries of large domes with four arches and pendentives, varying horizontal sections of piers were propagated, especially in asymmetrically organized structural schemes. The mosque of Fatih had two free-standing piers of unknown shape. The piers sustaining the main dome of Bayezıt II in Istanbul have slightly protruding cross-arms of approximately equal lengths, simple

in comparison with Hagia Sophia's composite piers. The piers of Süleymaniye are much closer to those of Hagia Sophia with their elongated plan and projections to support the bracing arches. Nevertheless, Sinan preferred a compact proportion for the horizontal section of this important component of the structure. Thus, he attained a form that could withstand heavier eccentric loads. Also, the Süleymaniye piers are tied to different vertical elements of the main structure, thereby attaining bonds that might be associated with the horizontal members of a frame. Twin bracing arches join the piers not only to the lateral buttress piers but also to the buttresses on the qibla and entrance walls and provide supports for the semidome squinches.

Buttresses

In Ottoman mosque architecture before the conquest of Constantinople, a developed buttressing system was not present, nor was this of prime necessity since the domes were, in general, small, or the walls alone were adequately designed to counteract the lateral forces. An exception was the Üç Şerefeli Mosque; it had a dome of considerable size, and buttresses were introduced on the qibla wall. This building bears witness to the fact that the Ottomans were in fact trying to construct buttresses of the correct size to stabilize domed structures of large dimensions. Since they did not have much experience in this field, they were not reckless in introducing major increases in dome sizes.

The basic idea of linking the main piers and the buttress piers by means of lateral arches and inserting side galleries in between was new for the Ottoman architects. In the mosque of Bayezıt II, these novelties are only partially incorporated into the structure. It took almost a century after the conquest for the Ottomans to gain mastery over buttresses and to manipulate them gracefully. Appreciating the architectural potential of these structural elements on side elevations, the architect Sinan combined them with decorative arcades and transformed them into meaningful features of the exterior. Though the slightly protruding buttresses on the exterior of Bayezıt are far from attractive, in Süleymaniye they are well proportioned and have become important members of the side elevations.

The buttresses on the western facade of Hagia Sophia triggered an interesting, singular repercussion in Ottoman architecture. This appears at the entrance facade of Piyale Paşa Mosque (1573–4), which has been stripped of its roofing (Figure 106). In Kılıç Ali Paşa Mosque a unique effect is achieved by the lateral buttresses of the main dome. These are in the form of arches attached to the main body of the structure in a highly exposed position as lateral supports to the main piers. The idea has similarities to the buttressing system of Hagia Sophia, where the buttress piers rise above the gallery level and are tied to the dome piers by walls and vaulting. This massiveness was never encouraged in Ottoman practice, and towering buttress piers were carefully avoided. When Kılıç Ali Paşa reverted to buttressing the dome base, a wide-spanned arch served to bond the outer pier to the main body (Figure 107).

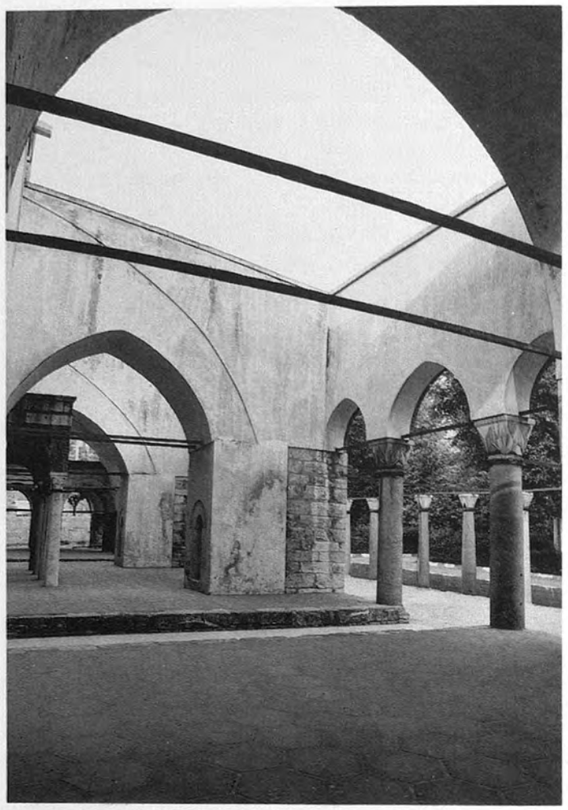

Fig. 106. Mosque of Piyale Paşa.

Galleries

Ottoman mosque interiors did not contain galleries until the mid-sixteenth century. There were small loggias or balconies, but they did not surround the central space. With the Süleymaniye, Ottoman mosques incorporated this feature into their structure. The construction of the floors and the system of vaulting for these galleries are quite interesting. In Kılıç Ali Paşa (Figure 108) and Mesih Paşa, cross-vaults were used for the purpose. The outer galleries of Piyale Paşa Mosque have a barrel vault intersected by two rows of lower spanned vaults, which are attached to the bordering arcade and wall, a type of vaulting that is quite uncommon for classical Ottoman architecture.

Flying Buttresses

Among the important structural details of the Ottoman mosques in Istanbul are the small buttresses at the window level of domes that abut the dome just above the level of the window arches. In general, they are in pairs at the four corners of the square dome bases. In structures with hexagonal and octagonal

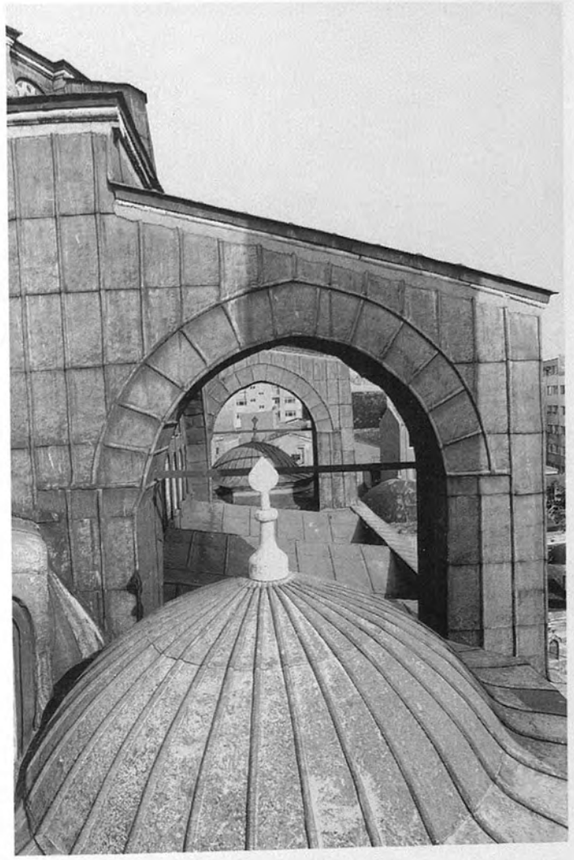

Fig. 107. Mosque of Kılıç Ali Paşa.

supporting systems, buttresses are dispersed around the dome, just above each of the main supporting piers.

Whether this is an idea springing from the structure of Hagia Sophia is not clear. The drawing of Sangallo (after Cyriacus of Ancona) furnishes graphic evidence for the presence of flying buttresses in Hagia Sophia before the conquest of Constantinople Cyriacus visited that city on several occasions.[17] He was present on the Turkish side during the siege of the city and died soon after. In the illumination of Seyyid Lokman dated 1581, which depicts the burial scene of Selim II, Hagia Sophia is shown with flying buttresses at the drum level.[18] In the seventeenth-century engraving of Hagia Sophia by Grélot, these are attached to the lateral buttress piers. The same features are present in the drawing of G. Fossati before the restoration in the nineteenth century.[19]

17 B. Ashmole, "Cyriac of Ancona," *Proceedings of the British Academy* 45 (1959), 25–41. A good rendering of Sangallo's drawing is in R. J. Mainstone, *Hagia Sophia: Architecture, Structure and Liturgy of Justinian's Great Church* (London: 1988), fig. 255.

18 Seyyid Lokman, *Şehname-i Selim Han*, Topkapı Palace Museum Library, A. 3595, fol. 156 r.

19 G. Fossati, *Aya Sophia, Constantinople* (London, 1852), plate 25.

Fig. 108. Mosque of Kılıç Ali Paşa.

The position of these buttresses is rather awkward; although the squinches at the junction of the dome base and the main buttress walls offer a supporting plane, the buttresses are not radially oriented to the dome center, as is the regular practice in Ottoman architecture. One reason for this solution could be the presence of another structure hindering the appropriate positioning (perhaps the turrets).

The earliest existing Ottoman dome with flying buttresses at drum level is the Üç Şerefeli Mosque in Edirne. Actually, the number and form of the flying buttresses in this building do not coincide with the tradition in the sixteenth century: The dome of Üç Şerefeli rests on six piers, but instead of six there are eight flying buttresses at drum level. They do not abut the dome below the drum cornice but rise above that level to meet the dome curve. The avant-garde nature of this mosque may provide an explanation for this unusual occurrence; another possibility is that these buttresses were inserted at a later date. Yet the accounts of the eighteenth-century restoration of this monument include the reconstruction of merely one single flying buttress. It is evident that the classical form of these structural elements evolved in Istanbul. The earliest appeared in the mosque of Fatih. The drawing of Matrakî is helpful for ascertaining the employment of flying buttresses at the base of the dome. In the mosque of Şehzade, they start from a lower level, breaking the severity of the cubic form below the dome. At Süleymaniye, a further step is taken; by the addition of flying buttresses to the lateral sides, visual and structural balance is achieved.

Turrets

Though not in the same position and relation to the main structure, the cylindrical turrets rising above the piers of the western semidome of Hagia Sophia

Fig. 109. Mosque of Bayezıt II.

may have served as a source of inspiration for similar details in Ottoman architecture. The stairways behind the pendentives of Hagia Sophia were also furnished with turret-like extensions above the level of the dome base. The Fossati brothers demolished the two on the eastern corners of the dome base. The drawings by Grélot and G. Fossati document a single rectangular turret on the southeastern corner. Whether they represent the form of original preconquest constructions or of early Ottoman insertions is not known. The drawing of Hagia Sophia's western elevation by Sangallo shows cylindrical turrets on the same level with the flying buttresses of the dome base. Either the dome base also had cylindrical features on the corners, or Sangallo's turrets represent those now flanking the western semidome. The present state of the stairways behind the pendentives is inconclusive, owing to the collapse of the upper parts of the stairs. In the mosque of Bayezıt II in Istanbul, turrets are positioned at the level of the dome base and, further down, over the lateral buttresses (Figure 109). These buttress turrets are vaguely indicated in the sixteenth-century drawing of Matrakî, which establishes their early origin before any restoration work was carried out in the eighteenth century. The

exact cylindrical form of these turrets may be another indication of their early date, whereas later, in the hands of Sinan, turrets became better proportioned and were integrated into the buttressing system of the superstructure.[20] More a structural sign than a load-exerting feature, their position over the main and buttress piers is well established after the sixteenth century.

Conclusion

The influence of a major monument like Hagia Sophia on Ottoman architects was inevitable. Ottoman architecture inherited Hagia Sophia and merged its ideals with this great structure. Ottoman architects gradually incorporated this complex body of knowledge into their construction methods in a steady line of development; the essence of innovation and experience present in Hagia Sophia's structure was slowly assimilated.

Ottoman architecture revived the structural principles of Hagia Sophia. The adoption of a dome on four supports as the central element of a mosque was the starting point. The transition elements were pendentives, and semidomes were integrated into the covering system.

Although Hagia Sophia inspired the building of wide-span interiors, Ottoman builders had to be careful in their choice of structural system. They tried to design more stable structures by choosing smaller sizes and improving buttressing systems. When one evaluates the position of Hagia Sophia in the development of Ottoman architecture, one comes to the conclusion that the disadvantages of this asymmetric organization hindered its wide-scale adoption. The favored schemes were centrally organized structures with four semidomes and with main domes supported by six or eight piers.

20 Stairs go up to the level of the dome base through the thickness of the sloping buttress wall, then go further in the wall of the dome base over the main lateral arches. The upper turrets have entrances that are today screened by the lead sheathing; there is no indication of a spiral stairway in or to the turrets.

THE LIFE OF AN IMPERIAL MONUMENT: HAGIA SOPHIA AFTER BYZANTIUM

GÜLRU NECIPOĞLU

Only a few great sanctuaries with a transcendent aesthetic quality have had a special propensity for adaptive reuse in different cultural and religious contexts. The afterlives of the Parthenon, first as a church, then as a mosque, of the Great Mosque in Cordoba, and of the Roman Pantheon as a church are examples that come to mind as parallels to the case of Hagia Sophia, transformed in 1453 into the foremost imperial mosque of Ottoman Istanbul after having served as the patriarchal seat of Eastern Christendom for nearly a millennium. The unusual resilience of the original sixth-century structure despite numerous later additions and changes is a tribute to Justinian and his architects, whose daring experiment in dome construction remained an unsurpassed feat for many centuries. Hagia Sophia's successive adjustment to modified circumstances and its capacity to absorb change while remaining essentially unchanged was due largely to an uninterrupted recognition of its unique formal qualities and its rich aura of symbolic associations through the centuries.

The 481-year-long life of Justinian's church as the mosque of Ayasofya deserves to be studied in greater detail than has thus far been attempted.[1] The various stages in the formal transformation and Ottomanization/Islamization of the post-Byzantine Hagia Sophia constitute an integral part of the monument's history. The layers of meaning the building acquired over the centuries transcended the specificity of the original context in which it was created and the chronological slot it occupies in the diachronic sequence of architectural history. To penetrate its historically mediated meanings one has to consider the influence and reception of Hagia Sophia after the Ottoman conquest of Constantinople and its sheer capacity to stand through time. The life of the

1 For preliminary studies of Hagia Sophia in the Ottoman period, see William Emerson and Robert L. Van Nice, "Hagia Sophia and the First Minaret Erected After the Conquest of Constantinople," *American Journal of Archaeology* 54 (1950), 28–40; Reşad Ekrem Koçu, "Osmanlı Devrinde Ayasofya," *İstanbul Ansiklopedisi* (Istanbul, 1960), 3: 1445–86; Tahsin Öz, *İstanbul Camileri* (Ankara, 1962), 1: 29–30; Wolfgang Müller-Wiener, *Bildlexikon zur Topographie Istanbul's: Byzantion, Konstantinopolis, Istanbul bis zum Beginn des 17. Jahrhundert* (Tübingen, 1977), 91–4.

monument involved a dynamic interaction with changing audiences and a lively dialogue between the past and present.

A Byzantine source suggests that nearly half a century before Mehmed II's conquest of Constantinople his great grandfather Bayezid I had already nursed the hope of converting Hagia Sophia into his royal mosque while contemplating its monumental glory from afar during an earlier siege of the city in the last decade of the fourteenth century:

> Au contraire, il [Bayezid I] menaça avec serment de s'emparer immédiatement de notre ville, s'il triomphait de ses ennemis, de transformer en mosquées pour les Agarènes tous les lieux saints de notre cité et, avant tout, la très grande église de la Sagesse de Dieu. . . . Posté sur une hauteur et contemplant les églises de la ville, il s'informait sur chacune d'elles et en demandait le nom. Il les distribuait à ses fils et à ses satrapes, se réservant pour lui uniquement la grande église de la Sagesse de Dieu. Voilà quel était l'objet de ses rêves et de son imagination, mais Dieu décidait de son sort et le destin, peut-on dire, se gaussait des espoirs de l'insensé.[2]

The singling out of Hagia Sophia as the church most suited to the sultan's dignity indicates an awareness of its special prestige. Bayezid I's premature dream was realized in 1453 when Mehmed II finally conquered Constantinople after yet another unsuccessful siege of the city by his father Murad II in 1422. When the victorious sultan made his formal entry into the vanquished city, he directly visited Hagia Sophia, the ruined state of which made him reflect on the transitoriness of worldly power and inspired melancholy meditations. With reference to the domed church and the nearby ruins of the Byzantine Great Palace he allegedly recited in Persian, "The spider serves as gatekeeper in the Arch of Chosroes, / The owl plays martial music in the castle of Afrasiyab," a distich that emphasizes the imperial associations of those monuments.[3] Like his grandfather, Mehmed II was quick to recognize Hagia Sophia's imperial prestige and monumental magnificence. Its imposing physical presence inevitably stimulated a dialogue with the Byzantine past that would bind the Ottoman rulers of Constantinople, which Mehmed II declared to be the new capital of his empire without changing its name (the official name Ḳoṣṭantiniyye continued to be used in Ottoman imperial documents and coins), to the classical imperial tradition. That tradition was subtly merged with the Turco-Islamic heritage of universal sovereignty and revived

2 P. Gautier, "Un récit inédit du siège de Constantinople par les Turcs (1394–1402)," *Revue des études byzantines* 23 (1965), 108–9. A similar story is related in a less reliable source, which claims that Bayezid I, gazing from a distance at Hagia Sophia, proclaimed it to be worthy of becoming his palace after his expected victory, cited in the Bulgarian Chronicle of 1296 to 1414, edited by J. Bogdan in "Ein Beitrag zur bulgarischen und serbischen Geschichtsschreibung," *Archiv für slavische Philologie* 13, no. 4 (1891), 540–2.

3 Cited in Tursun Beg, *The History of Mehmed the Conqueror by Tursun Beg*, facsimile and introduction by H. İnalcık and R. Murphy (Minneapolis, 1978), fol. 51a; and İdris-i Bidlisi, *Tercüme-i Heşt Behişt*, Ms. T.K.S.B. 196, fol. 80b. I thank John Pinto for bringing to my attention a similar passage from the *Commentaries* of Pius II, describing his visit to the ruins of Hadrian's Villa in 1461, which parallels Mehmed II's reaction to the ruins of Byzantine imperial monuments in 1453: "Time has marred everything. The walls once covered with embroidered tapestries and hangings threaded with gold are now clothed with ivy. Briars and brambles have sprung up where purple-robed tribunes sat and queens' chambers are the lairs of serpents. So fleeting are mortal things!" Aeneas Sylvius Piccolomini, *Memoirs of a Renaissance Pope: The Commentaries of Pius II*, trans. F. A. Gragg (New York, 1959), 193.

precisely at the moment when the classical past was being rediscovered in another part of the Mediterranean world, Renaissance Italy.

The contemporary court historian Tursun Beg describes how the awe-struck sultan wandered through the "paradise-like" Hagia Sophia with a group of learned men and dignitaries, contemplating the vastness of its "celestial dome," its patterned marble floors resembling the wavy sea, and its artistic gold mosaics. Tursun extolls the expert portraitist (*muṣavvir-i māhir*) who with pieces of colored glass had depicted on the summit of the dome the "portrait of an imposing man, so that it appeared to turn its face toward whatever direction one looked from," a reference to the illusionistic image of Christ Pantokrator, which the Muslim historian could not accept to be a representation of Christ as God. Tursun continues to describe how the "world emperor (*pādiṣāh-i cihān*)" climbed to the dome "as the spirit of God had mounted to the fourth story of the heavens," after he had observed from below the wonderful and strange figural mosaics. Having fully comprehended the significance of the building, the "emperor of the universe" ordered it to be repaired and transformed into his royal mosque.[4]

Mehmed II's aesthetic appreciation of Hagia Sophia is also confirmed in his *waqfiyya* (endowment deed), where it is referred to as the "exquisitely ornamented church (*kenise-i nefise-i münaḳḳāṣe*)."[5] The sultan's receptiveness to the formal values embodied in the building was natural given that Islamic–Ottoman architecture had for more than a century been experimenting with smaller domed mosques that culminated in the large domed space of the Üç Şerefeli Mosque in Edirne, built by Mehmed II's father between 1437 and 1447. The latter's monumentality might well have been a distant response to Hagia Sophia, which was not unknown to the Ottomans at that time. It may also have been inspired by the grand scale of contemporary Timurid domed buildings characterized by their multiple minarets, given the Ottoman preoccupation with the prestige of Timurid culture after the humiliating defeat of Bayezid I by Timur in 1402. Whatever its source of inspiration, the Üç Şerefeli Mosque architecturally expressed growing imperial claims justified by the rapid expansion of the Ottoman Empire. Its monumental hemispherical dome and its atrium-like columned courtyard with a fountain at the center (used in a royal mosque for the first time) were part of a classical Mediterranean language of forms creatively synthesized with the Islamic–Ottoman architectural heritage.

Shared architectural idioms and a familiarity with Hagia Sophia's imperial iconography were important factors that contributed to its preservation by Mehmed II, who began to see himself as legitimate heir to the Byzantine emperors after conquering Constantinople. This is acknowledged by the humanist George of Trebizond, who wrote in his Latin treatise (*On the Eternal Glory of the Autocrat and His World Dominion*), which he dedicated to the sultan in 1466 with the hope of converting him to Christianity before he conquered Rome, "All the Westerners agree that in Constantine's time the universal kingdom passed to that city which as a grace from God you now rule (hence no one can doubt that in accordance with the laws handed down to us by our

4 Tursun, *The History of Mehmed the Conqueror*, fols. 51a–53a. The same tour is described in Bidlisi, *Tercüme-i Heşt Behişt*, fols. 79v–91r.

5 *Fatih Mehmed II Vakfiyeleri* (Ankara, 1938); Tahsin Öz, ed., *Zwei Stiftungsurkunden der Mehmed II* (Istanbul, 1935).

forefathers you are the king of the world)." Inspired by the lives of Hannibal, Caesar, and Alexander the Great, which two readers in Greek and Latin daily read to him, Mehmed II was fired by an ambition to reunite Constantinople and Rome under a world empire unified by a single monarch and a single religion. European efforts to convert him to Christianity proved futile; the sultan was strongly committed to the glory of Islam. His restoration of Hagia Sophia as his royal mosque was part of an ambitious program to restore the new Ottoman capital to its former magnificence and prosperity in the golden age of the Byzantine Empire, so that it would become a proper center for the world empire he sought to create. In this unique building, past and present were juxtaposed to invite a recognition of the Ottoman sultans as the successors of the Byzantine emperors and of the triumph of Islam over Christianity. This theme was also emphasized by the sultan's decision to model his own funerary mosque complex built between 1463 and 1470 to replace the Church of the Holy Apostles, where the Byzantine emperors used to be buried, after the Hagia Sophia. That this was a conscious decision is revealed by Tursun Beg's description of the building as a "great mosque based on the design of Ayasofya (*Ayaṣofya kārnāmesi resminde*) which not only encompassed all the arts of Ayasofya, but moreover incorporated modern features constituting a fresh new idiom (*nevʿ-i şīve-i tāze*)." Thus, Mehmed II initiated an ongoing dialogue between the Islamic–Ottoman architectural heritage and Hagia Sophia that would give birth to a new series of sultanic mosques visually expressing the dialectic link between the past and present through a unique stylistic synthesis.[6]

Constructing the Myth of Hagia Sophia

To facilitate the reconsecration of Hagia Sophia and Constantinople in the new Islamic context – a project reminiscent of the task Constantine the Great faced when he appropriated the pagan city – Mehmed II ordered a group of Greek and European learned men, patriarchs, and priests to write a history of the emperors who built the city's astonishing monuments, which no longer appeared to be man-made. The earliest surviving Turkish and Persian versions of this text composed in 1479 and 1480 are based largely on the Byzantine ninth-century *Diegesis peri tes Hagias Sofias* (Narrative concerning Hagia Sophia), of which a Greek copy written for Mehmed II in 1474 survives among the royal manuscripts of the Topkapı Palace. Other versions of the text, supplemented with newly invented traditions of popular piety, were composed soon after the death of Mehmed II and incorporated into a large number of

6 John Monfasani, ed., *Collectanea Trapezuntiana: Texts, Documents, and Bibliographies of George of Trebizond* (Binghamton, N.Y., 1984), 494. For Mehmed's two readers and his imperial ambitions, see the report of Giacomo Languschi from 1453, published in Agostino Pertusi, *Testi inediti e poco noti sulla caduta di Costantinopoli*, ed. posthumously A. Carile (Bologna, 1983), 172–5. The sultan's project for restoring Constantinople is described in *History of Mehmed the Conqueror by Kritovoulos (1451–1467)*, trans. C. Riggs (Princeton, N.J., 1954), 104–5, 140–1. For Mehmed II's mosque complex in Istanbul, see Tursun, *The History of Mehmed the Conqueror*, fols. 58a–58b. For a recent discussion of the impact of Hagia Sophia on Ottoman mosque architecture, see Rowland J. Mainstone, *Hagia Sophia: Architecture, Structure and Liturgy of Justinian's Great Church* (London 1988), 237–59.

late-fifteenth- and sixteenth-century Ottoman chronicles.[7] It was to a large degree these widely circulated texts that helped instill in the popular imagination the image of Hagia Sophia as a mosque.

In these texts history and myth are combined in an attempt to interweave Constantinople and Hagia Sophia into both a pre-Christian mythical past and an Islamic present to complement their dominant Christian–Byzantine memory. Constantinople is described as a great historical city founded by the mythical ruler Yanko bin Madyan, a descendant of the Persian emperor Shaddad, who was divinely guided by a dream to build a wonderful city where two seas meet. By tracing the periodic destructions of Constantinople and its subsequent rebuilding by great sovereigns like Solomon, Constantine, and Justinian, the texts place the city's history in a cyclical scheme of universal cosmography. Following several unsuccessful Arab attempts to conquer Constantinople, Mehmed II's victory fulfills the Prophet Muhammad's prophecy that the city would one day be conquered by Muslims: "They will conquer Constantinople. Hail to the Prince and the army to whom this is granted." The sultan's subsequent rebuilding of Constantinople thus marks the beginning of a new Islamic epoch that had been foreshadowed in the days of the Prophet.

These mythical Ottoman histories attempt to justify Hagia Sophia's conversion into a royal mosque by complementing its Christian associations with Islamic ones and by emphasizing its prestigious imperial past, which made it a potent symbol of universal sovereignty. Some versions invent the tradition that it was constructed with spolia from structures built by Solomon (revered as a prophet in the Islamic tradition) on a site originally sanctified by him, a reference meant to strengthen the royal connotations of the palatine church juxtaposed to the ruins of Constantine's Great Palace, next to which Mehmed II built his own palace, the Topkapı, between 1459 and 1479. According to Şemsüddin's version of 1480, Justinian in a dream is urged by God's immortal messenger Hızır (Elias) to build the church according to a divinely inspired plan on the site of an ancient temple that would demonstrate the triumph of Christianity over paganism following his supression of a pagan revolt. After demolishing the temple of the defeated idol worshipers on that site, the victorious emperor writes to the "kings of the seven climes," ordering them to

7 The original Greek text is published in Théodor Preger, *Scriptores Originum Constantinopolitanarum*, 2 vols. (Leipzig, 1901–7); it is translated into French and analyzed by Gilbert Dagron, *Constantinople imaginaire: Études sur le recueil des Patria* (Paris, 1984), 191–314. For the early Ottoman texts on Hagia Sophia by Yusuf bin Musa (1479) and Şemsüddin (1480), see Felix Tauer, "Notice sur les versions persanes de la légende de l'édification d'Ayasofya," in *Fuat Köprülü Armağanı* (Istanbul, 1953), 487–94; idem, "Les versions persanes de la légende sur la construction d'Aya Sofya," *Byzantinoslavica* 15 (1954), 1–20; Paul Wittek, "Miscellanea; 2. Zu den persischen Tarih-i Ayasofya," *Türkiyat Mecmuası* 14 (1964), 266–70. For a later account of Constantinople and Hagia Sophia incorporated into an anonymous Ottoman chronicle in 1491, translated into French with a detailed analysis of its sources and textual variants, see Stephane Yerasimos, *Légendes d'empire: La fondation de Constantinople et de Sainte-Sophie* (Paris 1990). Yerasimos's translation is based on the edition of Friedrich Giese, *Die altosmanischen anonymen Chroniken:* part 1: *Text und Variantenverzeichnis* (Breslau, 1922), 71–111; in this essay I will cite Yerasimos's convenient French translation (thereafter *Légendes*).

I started a comparative study of Persian and Turkish manuscripts on Hagia Sophia in 1985–6, as part of a postdoctoral research project that was awarded a Mellon Fellowship at the Society of Fellows in the Humanities at Columbia University. Together with the Greek *Diegesis* written in 1474 for Mehmed II (Topkapı N6) these texts still await a critical edition, a difficult task given the large number of variants listed in *Légendes*, pp. 250–6.

contribute to the construction of Hagia Sophia by sending rare stones removed from the ancient pagan temples of India, Arabia, Yemen, Maghrib, Persia, China, Turkistan, Byzantium, and Europe. In this way Justinian's monumental church is reconstituted in the Ottoman text as a symbol of universal rule that reflected a perfect concordance between divine will and imperial power.[8]

The original construction of Hagia Sophia signified the triumph of Christianity over paganism under Justinian; its second consecration as Mehmed II's royal mosque represented the final victory of Islam that had been predicted by various signs. The Ottoman texts claim that the half-dome above the apse of Hagia Sophia had collapsed on the night of the Prophet Muhammad's birth, together with many other churches and Sassanian monuments including the Arch of Chosroes. Attempts to rebuild it were unsuccessful until a Byzantine embassy was sent to the Muslim Prophet, who sanctioned its reconstruction, knowing that it would someday serve Muslim congregations.[9] Thus, the new dome was held in place by the Prophet's miracle and, according to one version of the legend, by a special mortar compounded of sand from Mecca, water from the holy well of Zemzem at the Ka'ba, and the Prophet's saliva.[10]

This myth is developed further in the story of Abu Ayyub al-Ansari, one of the Prophet's companions, who had made an agreement with the Byzantine emperor to stop his siege of Constantinople in return for permission to pray in Hagia Sophia, an unusual request prompted by the Prophet's prophecy that the church was predestined to become a mosque and that whoever prayed in it would go to paradise. Ayyub was the first Muslim to pray there before he was martyred by the Byzantines, who buried him outside the city walls. His tomb was miraculously discovered and rebuilt by Mehmed II soon after the conquest of Constantinople, when it became the center of an imperially sponsored cult that played an important role in sanctioning Ottoman rule in the Islamized city. In it the sultans were girded with the sword of sovereignty after their accession to the imperial throne.[11]

The earlier consecration of Hagia Sophia by the Prophet and by a Muslim martyr helped legitimize its conversion into a mosque with no radical changes in its structure or decorative program. Şemsüddin writes that both its plan and the name Ayasofya (understood at that time to mean the "House of Worship [*'ibādetgāh*]" of God) had been divinely communicated to Justinian through Hızır in a dream. He adds that this is why the mosque continued to be called by the same name, a continuity implying that Hagia Sophia had always been

8 For references to Solomon in the anonymous chronicle of 1491 and a summary of Şemsüddin's version, see *Légendes*, 6–7, 27–8, 113–23.

9 Ibid., 36.

10 The use of mortar made up of Meccan earth, Zemzem water, and the saliva of the Prophet is mentioned in the seventeenth-century travelog of Evliyā Çelebi, *Seyāḥatnāme* (Istanbul, 1896), 1: 124–5; also see F. W. Hasluck, *Christianity and Islam under the Sultans* (Oxford, 1929), 1: 11. According to one source, seventy camel-loads of water from the holy well of Zemzem and seventy camel-loads of earth from Mecca were dispatched for the mortar; Hasan Özdemir, *Die altosmanischen Chroniken als Quelle zur türkischen Volskunde*, Freiburg-im-Breisgau, Islamkundliche Untersuchungen, 32 (1975), 169. For the urban folklore of Istanbul, see H. Russack, *Byzans und Stamboul, Sagen und Legenden vom Goldenen Horn* (Berlin, 1941).

11 For the story of Ayyub and the Arab sieges of Constantinople, see *Légendes*, 38–48, 160–82; M. Canard, "Les expéditions des Arabes contre Constantinople dans l'histoire et dans légende," *Journal asiatique* 208 (1926), 61–121.

the sanctuary of the same God worshiped by Christians and Muslims alike.[12] Many of the Christian legends attached to the building were similarly appropriated by Muslim popular piety, such as the story of the doors said to be constructed from the wood of Noah's ark, in front of which the opening sura of the Koran (Al-Fatiha) was recited before a voyage, or of water from the sacred well seen as a cure for palpitations, or of the sweating column of St. Gregory (now associated with Hızır), which also had curative powers. These were complemented by an ever-growing series of new legends. The praying places (*maḳām*) of Muslim martyrs like Ayyub, Sayyid Battal Ghazi, and others who fought in the Arab sieges of Constantinople were regularly pointed out to Muslims and foreign travelers by mosque attendants, well versed in popular legends concerning Hagia Sophia that constituted a continually elaborated collection of urban lore. When Reinhold Lubenau came to Istanbul with an embassy from the Hapsburg emperor Rudolf II in 1587–9, he was taken around Hagia Sophia and shown, among other wonders, the stone cradle of Christ; he was also told about the simultaneous collapse of Hagia Sophia's dome and the Arch of Chosroes on the day of Muhammad's birth and other "wonderful fables."[13]

These fables played a central role in making Hagia Sophia an integral part of the Ottoman collective memory. By the early sixteenth century, the court historian İdris-i Bidlisi could compare the special sanctity of the mosque to that of the Ka'ba and the Aqsa Mosque, the holiest Muslim sanctuaries. Other sixteenth-century authors repeat the comparison with the Aqsa Mosque and refer to Hagia Sophia as the second Ka'ba for the poor who could not afford the pilgrimage to Mecca.[14]

Numerous encomiums were composed by Ottoman poets about Hagia Sophia in the *Şehr-engiz* literature of Istanbul, a poetic genre that praises the beauties of the city, including both its outstanding monuments and inhabitants. In his poem of 1493–4, entitled "Attributes of Ayasofya," Cafer Çelebi praises the cosmic features of the mosque's monumental construction, the patterns of its precious marble revetments resembling the waves of the sea, its vast interior space covered by a colossal celestial dome, its artistic gold mosaics, its columns and arches, which seemed to bow and rise up in the worship of God, as well as its beautiful minbar, mihrab, and loggia (mahfil) from which the Koran was recited. Noting that the name Ayasofya means "place of worship (*cāy-i 'ibādet*)" of God for the pious, the court poet concludes that though there may be many other holy mosques covered with high domes, this one is the "victorious Shah of them all" (a claim repeated by the nineteenth-century author Müstakimzade, who refers to Hagia Sophia as the

12 From an anonymous Turkish translation of Şemsüddin's Persian text based on the Greek *Diegesis* written for Mehmed II, *Terceme-i tārīḫ-i cāmi'-i Ayaṣofya li Dervīş Şemsü'd-dīn Ḳaramānī*, Istanbul University Library, Ms. T. 259, fol. 19; cited with a slightly different translation in *Légendes*, 119–20.

13 For the continuity of Christian traditions and the invention of new ones by popular piety, see Hasluck, *Christianity and Islam*, 1: 10–13; Evliya, *Seyāḥatnāme*, 1: 133–6. Popular traditions reported by pilgrims before the Ottoman conquest are conveniently compiled in George P. Majeska, *Russian Travelers to Constantinople in the Fourteenth and Fifteenth Centuries* (Washington, D.C., 1984). The role of mosque attendants in perpetuating the popular stories can be deduced from Reinhold Lubenau, *Beschreibung der Reisen des Reinhold Lubenau (1573–1589)*, 2 vols., ed W. Sahm (Königsberg, 1912–20), 1: 143–6.

14 Bidlisi, *Terceme*, fol. 80a. For the same comparison made by Celālzāde, Lātifi, and Taşlıcalı Yahya Bey, see Asaf Halet Çelebi, *Divan Şi'rinde İstanbul* (Istanbul, 1953), 37, 39, 40–1.

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"commander of all mosques"). The late-seventeenth-century court poet Nabi also stresses the special sanctity of Hagia Sophia that makes prayer in it "a hundred times more valuable" than in any other mosque.[15]

These poems and the continuous life of Hagia Sophia as a mosque for nearly half a millennium testify to the success of its mythical history, which was originally part of Mehmed II's efforts to legitimize the preservation of the Byzantine church as the main imperial mosque of the new Ottoman capital. The text commissioned by the sultan was much closer to its ninth-century Byzantine model than its other versions to which new oral traditions invented by folk piety were freely incorporated. The original text written for Mehmed II and translated into Persian in 1480 by Şemsüddin had primarily stressed the triumphal aspects of Justinian's divinely inspired imperial church (built with spolia that the tributary kings of the seven climes had sent to commemorate the emperor's victory over pagan rebels) to highlight the sultan's own political ambitions. It confirmed how closely the conversion of Hagia Sophia to the sultan's mosque was associated with his imperial policy, which marked the graduation of the Ottoman state from a modest principality to a world empire. Different versions of the text, which proliferated soon after Mehmed II's death in the late 1480s and 1490s, change the emphasis from the *regal* to the *sacred* associations of the building through new traditions of Muslim popular piety. Radically departing from the original Greek text, they go as far as attributing the construction of Hagia Sophia to the will of Constantine's pious wife Asafiya, after whom the monument was allegedly named, an attempt to underplay its connection with the powerful emperor Justinian. These texts, which lived side by side with versions elaborating the one composed for Mehmed II, are characterized by an antiimperial sentiment reflecting the popular resentment of those opposed to the conqueror's new imperial image so different from that of his more egalitarian forebears. The mosque that had been Ottomanized by Mehmed II thus took a much longer time to Islamize.[16]

Changes in the Architecture and Decoration of Hagia Sophia

The symbolic appropriation of Hagia Sophia by the new dynasty and faith through the "invention of tradition" was complemented by subtle changes in its architecture and decoration over the centuries. According to popular legend, this process of physical transformation began even before the church had been converted to a mosque. The seventeenth-century Ottoman traveler Evliya Çelebi claims that an architect named Ali Neccar, whom Mehmed II had sent to the Byzantine emperor to repair Hagia Sophia (damaged by an earthquake three years before the city's conquest), informed the sultan on his return to Edirne: "I have secured the cupola of Ayasofya, O Emperor, by four mighty buttresses; to repair it depended on me, to conquer it depends on

15 Cafer Çelebi's poem is published in Agah Sırrı Levend, *Türk Edebiyatında Şehr-Engizler ve Şehr-Engizlerde İstanbul* (Istanbul, 1957), 76–8. See Süleymān Saʿaded-dīn Efendi [called Müstaḳīmzāde], *Tuḥfet'ül-haṭṭaṭīn* (Istanbul, 1928), 78; and Nabi's poem published in Asaf Halet Çelebi, *Divan*, 65. For other encomia on Hagia Sophia, see Ibid., 39, 41–2, 48–9, 65; Koçu, *İstanbul Ansiklopedisi*, 3: 1469–71.

16 The reference to Asafiya is found in the anonymous version of 1491, *L égendes*, 24. For Yerasimos's interpretation of the antiimperial ideology inherent in some texts, see ibid., 2–3, 123, 133–59, 247–9.

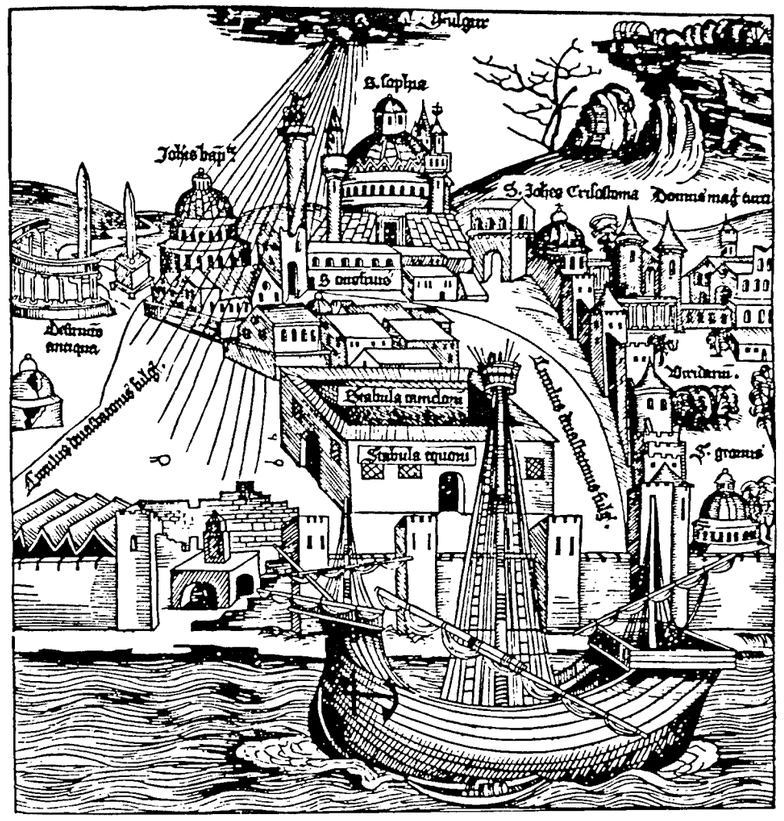


Fig. 110. Hagia Sophia and its first two minarets, with the Topkapı Palace to the right and the Hippodrome to the left. (From Hartmann Schedel, *Liber Chronicarum*, 1493)

thee. I have also laid the foundations of a minaret for thee, where I offered up my prayers." The buttress, which the architect had provided with a staircase, allegedly served as the foundation of a minaret that Mehmed II built after the city was conquered. Thus, every detail played a part within a predestined scheme that finally culminated in the inevitable conversion of Hagia Sophia to a mosque.[17]

Mehmed II attached only a few potent signs of Islam onto the preexisting fabric of the church, once it had been emptied of its relics, crosses, and icons. He added the first two minarets, which signified that the building was now an imperial mosque (only persons of royal Ottoman blood could use more than one minaret), removed the bells from its belltower, and the cross at the summit of its dome (Figure 110). Behind the mosque he had a madrasa built for the study of Muslim theology. To the mosque's interior he added a marble minbar and mihrab (still in situ), which had to be placed at an angle since the apse of the church was not aligned with Mecca. Consequently, as the

17 Evliya Çelebi, *Narrative of Travels in Europe, Asia and Africa in the Seventeenth Century*, trans. J. von Hammer-Purgstall (London, 1834), 57; cited in Emerson and Van Nice, "Hagia Sophia and the First Minaret," 29–30.

nineteenth-century traveler Edmondo de Amicis notes, the mats and strips of carpets had to be "placed obliquely with the lines of the building, and produce upon the eye some gross defect in perspective." The figural mosaics on the lower levels were immediately plastered over, but the ones situated above or beyond the view of the praying congregations survived almost intact well into the sixteenth century. They were complemented by a few unobstrusive Muslim inscriptions that helped announce the new identity of the building.[18]

Inside the mosque Mehmed the Conqueror also placed Muslim relics and mementos of victory, including one of the four prayer carpets of the Prophet hanging to the right of the mihrab and his own banners of victory commemorating the conquest of Constantinople. The latter were attached to both sides of the minbar where the *khatib* read the *khutba* each Friday with a drawn sword in his hand signifying that Hagia Sophia was a mosque acquired through holy warfare. The mosque was also associated with the conquest of Constantinople through its enormous *waqf;* Mehmed II dedicated all the income from shops and other property that fell to his share in the vanquished city for its upkeep.[19]

Emblems of conquest continued to accumulate inside the mosque: In 1526 Süleyman the Magnificent offered as *waqf* to it two enormous bronze candlesticks removed from the cathedral of Buda as a trophy of his conquest of the Hungarian kingdom. They still flank the mihrab, inscribed with verses referring to the victory of the "world emperor" Süleyman, the death of the Hungarian king, and the destruction of Hungary's churches. They end with the chronograms "Let the candle of religion shine forever" and "Let the candle of the light of Islam be eternal," both yielding the date 933 (1526–7).[20]

The church that Justinian had built to commemorate the triumph of Christianity by incorporating into its structure marbles and spolia from pagan monuments thus came to represent the glory of Islam through new spoils of victory. Throughout the sixteenth century, when Ottoman dynastic legitimacy was still based largely on successful military expansion through holy warfare (*ġazā*), Hagia Sophia continued to be a meaningful commemorative monument celebrating the triumph of Islam under the aegis of the victorious Ottoman dynasty. Its architecture and mosaic decoration were preserved as the brilliant mementos of the subjugated Christian–Byzantine past, the memory of which was still very much alive and encouraged the hope of future victories to come.

18 Edmondo de Amicis, *Constantinople,* 2 vols. (Philadelphia, 1896). For the preservation of the mosaics, see Cyril Mango, *Materials for the Study of the Mosaics of St. Sophia at Istanbul* (Washington, D.C., 1962). That some of the mosaics had been covered up by Mehmed II is demonstrated by Marino Sanuto's report referring to an earthquake in 1509 when images reappeared under the falling plaster; cited in ibid., 99, 118. Bidlisi notes that some of the mosaics in the mosque were replaced by Muslim inscriptions; *Tercüme-i Heşt Behişt,* fols. 79v–91r. These early inscriptions are attributed to Mehmed bin Hamdi bin Mehmed bin Hamza (d. 909/1503–4), a descendant of Akşemseddin, Mehmed II's revered teacher, who was assigned the professorship of the madrasa of Hagia Sophia; see Müstaḳīmzāde, *Tuḥfe,* 442.

19 The Prophet's carpet and Mehmed II's banners are mentioned in H. G. Samuelyan, *The Mosque of St. Sophia* (New York, 1890), 6; and in De Amicis, *Constantinople,* 1: 259. Lubenau says the banners were green and black; *Beschreibung,* 1: 144. For the enormous *waqf* of Hagia Sophia, see Mehmed II's *waqfiyya*s cited in note 5; the *waqfiyya* of Hagia Sophia is preserved in Atatürk Kütüphanesi, Istanbul, Ms. Muallim Cevdet 0.41; and another *waqf* register of Hagia Sophia compiled in 1490 is in Başbakanlık Arşivi, Maliyeden Müdevver 16.

20 For the candlesticks and their inscriptions, see Koçu, *İstanbul Ansiklopedisi* 3: 1471; İbrāhīm Peçevī, Tārīḫ, 2 vols. (Istanbul, 1864–7), 1: 100.

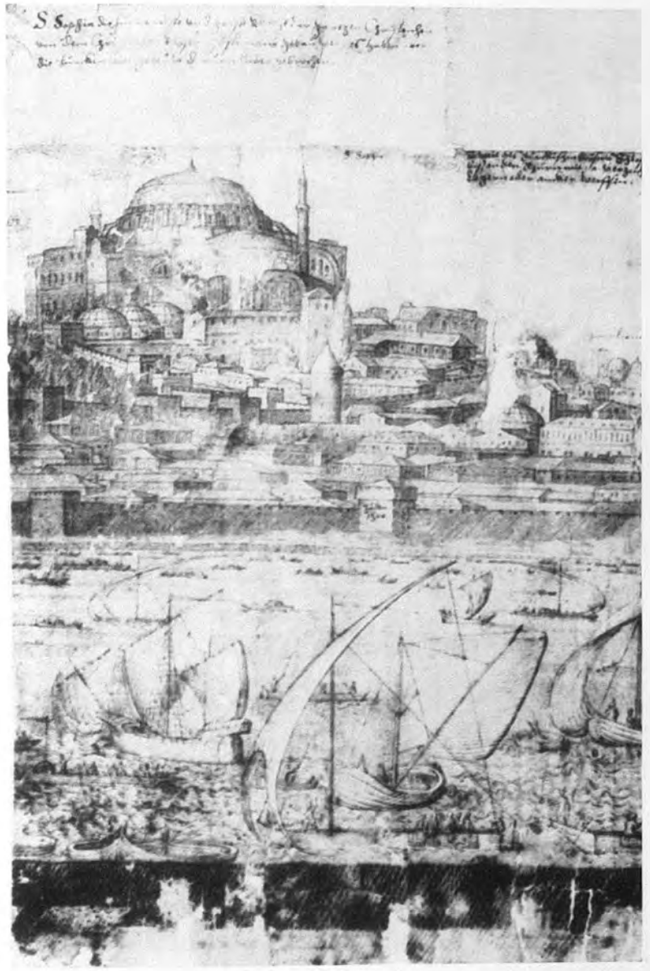


Fig. 111. Melchior Lorch, Hagia Sophia, ca. 1559. (From E. Oberhummer, *Konstantinopel unter Sultan Suleiman dem Grossen,* Munich, 1902)

More than a century had passed since the reconsecration of Hagia Sophia as a mosque when Selim II undertook the first large-scale renovation of the building in 1572–4 (Figures 111 and 112). Mimar Ahmed, the architect in charge of Hagia Sophia's maintenance, prompted the project when he informed the sultan that the building needed extensive renovation. Four firmans of Selim II, only two of which have been published, document the sultan's efforts to reinforce the threatened monument. The first two inform the qadi of Istanbul in April 1572 (Zilhicce 979) that Mimar Ahmed (Ayaşofya Miʿmarı Aḥmed) had complained that houses, rooms, latrines, and kitchens had been built adjacent to or were encroaching onto the walls of the mosque, a situation confirmed by an inspecting committee that included the *naib* and the mosque's imam. The qadi is ordered to have these structures demolished. The third firman from April 1573 (Zilhicce 980) is addressed to

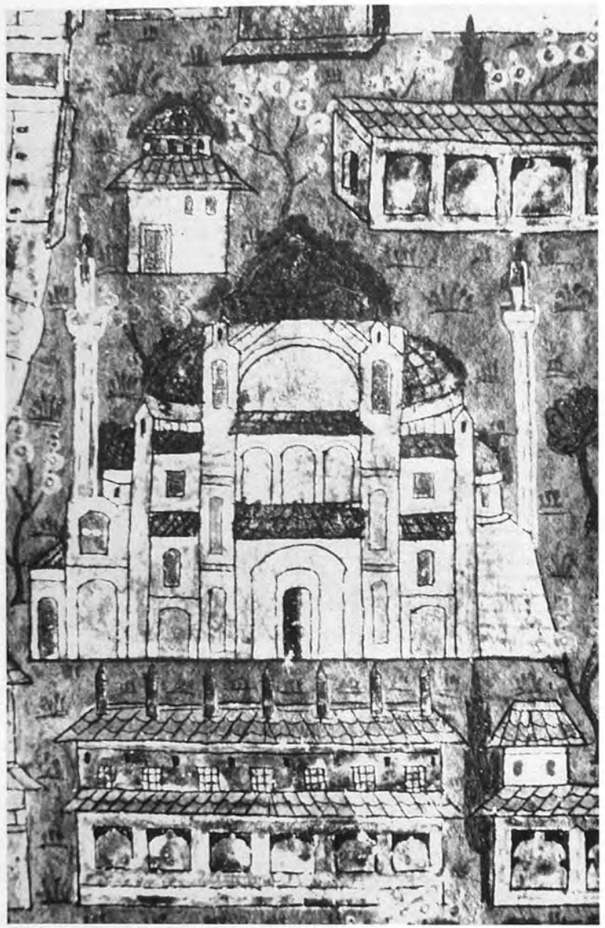


Fig. 112. Matrakçı Nasuh; detail of Hagia Sophia from map of Istanbul, ca. 1536. (From H. G. Yurdaydın, *Beyan-i Menazil-i Sefer-i Irakeyn,* Ankara, 1976)

the *waqf* administrator (*mütevellī*) of Hagia Sophia and to the royal architect Mehmed (Ḥāṣṣa miʿmarı üstād Meḥmed). It reports that the administrator had sent the sultan a letter about the need to repair the mosque's crumbling buttresses and to rebuild in brick the dilapidated wooden minaret that had been hastily added to the church after the city's conquest. It therefore orders the architect Mehmed to construct an appropriate base for the new minaret and to repair the buttresses with utmost care.[21]

The fourth firman was issued three months later in June 1573 (Safer 981). It informs the qadi of Istanbul and the *waqf* administrator that the sultan had inspected the building with a committee of experts, including the chief archi-

21 The first two unpublished firmans are in Başbakanlık Arşivi, Istanbul, Mühimme Defteri 10, no. 291, and Mühimme Defteri 16, no. 375. The third one (Mühimme Defteri 21, no. 615) is published in Ahmet Refik, *On Altıncı Asırda İstanbul Hayatı,* no. 14 (Istanbul, 1935), 21, and partially translated into English in Emerson and Van Nice, "Hagia Sophia and the First Minaret," 33.

tect Sinan, and had come to the conclusion that a space of 35 cubits should be cleared to the right and left of the mosque, that a 3-cubit passage should be left around the madrasa, that the neighboring royal warehouse must be demolished, that the minaret on top of the half-dome should be eliminated and replaced by another minaret built on top of the buttress in front of it, that buttresses and water conduits should be built in the 35-cubit-wide open space around the mosque, that places in need of repair inside and outside the mosque should be restored and cleaned, that the stone and brick obtained from the demolished structures abutting the mosque should be used in the repairs, and that the lead covering the dome should be renewed. The firman also stipulates that the continuous row of buildings with shameful latrines that had appropriated spaces between the buttresses, or had been carved into them in ways that threatened the mosque's stability, should forthwith be removed. According to a *fatwa* (legal opinion) obtained from the Şeyhülislam, even those squatters who had sold stones and bricks removed from the buttressing to build their own wooden or mudbrick houses were going to be recompensed with indemnities. However, the royal firman concludes, those who opposed the sultan's orders as tyranny, arguing that Hagia Sophia need not be preserved since it had been built by non-Muslims, deserved to be executed as infidels.[22] This last point shows that, despite largely successful official efforts to Islamize the building, its Christian memory had not completely been erased.

As these firmans suggest, Selim II's efforts to consolidate the structural stability of Hagia Sophia by strengthening its buttresses and building a minaret on one of them were on a massive scale. The contemporary historian Selaniki notes that the more than a millennium old building had not been repaired since the days of Mehmed II; it was surrounded by houses on all sides and faced imminent collapse, already leaning about 1.5 cubits to one side. When the surrounding structures were demolished, an army of martens, rats, and bats fled through the neighborhood. After inspecting the building with his grandees, the sultan ordered Sinan to build powerful buttresses around it. Giving the architect a robe of honor, he said, "It is my wish to renovate the noble mosque in order to make it my own royal monument," a clear indication that the sultan wanted to place his personal stamp on the prestigious building.[23]

Peçevi and Mustafa Āli, two other contemporary historians, bring out the hitherto unnoted fact that Selim II had also commissioned Sinan to build two new minarets in addition to the pair that he had repaired, two Selimiye madrasas, and a mausoleum in the walled-in space that had been cleared up around the mosque.[24] The project conceived by Selim II was left partially incomplete

22 Başbakanlık Arşivi, Istanbul, Mühimme Defteri 22, no. 171; published in Refik, *On Altıncı,* no. 18 (1935), 22–4, and partially translated in Emerson and Van Nice, "Hagia Sophia and the First Minaret," 33–4.

23 "Murādım cāmiʿ-i şerīfi iḥyā' idüb eşer-i ḫāṣṣ idinmekdür," Muṣṭafā Selānikī, *Tārīḫ* (Istanbul, 1864–5), 120–1.

24 Peçevi describes Selim II's renovation under the chapter title "The Construction of Buttresses and Two New Monumental Minarets at the Noble Mosque of Ayasofya." He writes that in "the year 981 (1573–74): A decree was issued by Sultan Selim Khan . . . ordering the construction of great buttresses as a safety measure for the colossal dome of the noble Ayasofya mosque, two unequaled minarets, two lofty madrasas, and a noble mausoleum for his burial. These were completed in a short time except for the mausoleum, which was finished posthumously"; Peçevī, *Tārīh,* 1: 501. Mustafa Āli says that after properties adjacent to the mosque were bought, a space 40 cubits wide

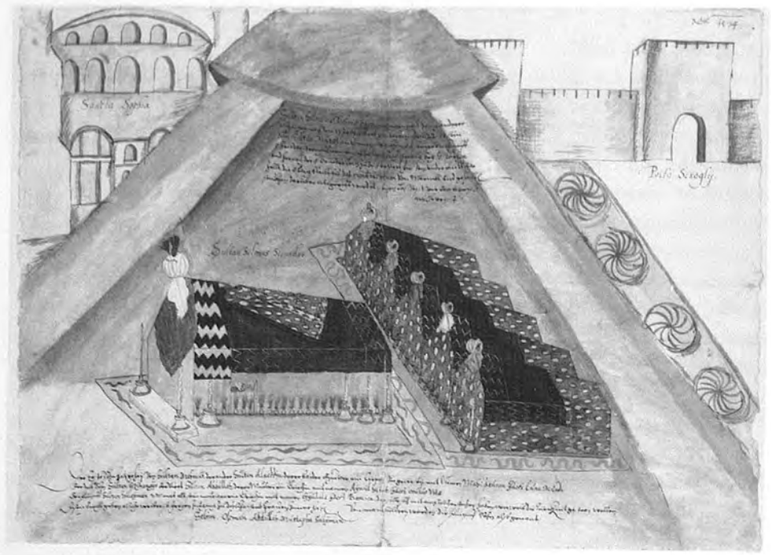


Fig. 113. Burial tent of Selim II and the royal princes, ca. 1574. (From the Freshfield Album, Trinity College Library, Cambridge, p. 45, ms. 0.17.2)

when he died a year later in 1574. That the mausoleum, whose site had already been selected, was built posthumously is confirmed by a folded drawing in the so-called Freshfield Album, made by an anonymous German artist in December 1574. Behind the south facade of Hagia Sophia, on the spot where Sinan later built Selim II's mausoleum (completed in 985/1577), the drawing shows a temporary red tent over the coffins of Selim II and his five sons (Figure 113).[25] This is in keeping with the common Ottoman practice of constructing royal tombs only after the death of each sultan; a miniature in the Chester Beatty *Süleymānnāme* shows that a similiar imperial tent had been temporarily raised behind the Süleymaniye Mosque over the site where Sinan later built Süleyman's domed mausoleum.[26]

While the two madrasas named after Selim II were never completed, the two new minarets he commissioned were built, together with his projected mausoleum, by his son Murad III. This is demonstrated by another folded drawing in the Freshfield Album, which depicts Hagia Sophia with only two

was opened up around the building and enclosed by an elegant wall (*sūr-i laṭīf*). "Then the construction of buttresses abutting the dome of Ayasofya and the building of two new minarets in addition to the two existing monumental minarets was ordered. A pleasant site for his burial place was designated and in addition to the old madrasa the construction of two exalted Selimiye madrasas (*iki medrese-i celīle-i Selīmīyye*) was commanded as well. But since his blessed lifetime did not suffice, God enabled him to realize merely the beginning of the construction of those two madrasas while the rest of the conceived parts had been fully planned"; Muṣṭafā ᶜ ʿĀlī Gelibolulu, *Künhü'l-aḫbār*, İstanbul Üniversitesi, Ms. T.Y. 5959, fol. 459v.

25 The princes were strangled by their brother Murad III soon after his accession to the throne according to a dynastic tradition instituted to stop struggles for succession among the princes. For the Freshfield Album (Trinity College, Cambridge, Ms. 0.17.2), see E. H Freshfield, "Some Sketches Made in Constantinople in 1574," *Byzantinische Zeitschrift* 30 (1930), 519–22; Cyril Mango, "Constantinopolitana," *Jahrbuch des Deutchen archäologischen Instituts* 80 (1965), 305–36.

26 For Süleyman's burial tent, see Loḳmān, *Süleymānnāme*, dated 1579–80, Chester Beatty Library, Ms. 413, fol. 115b.

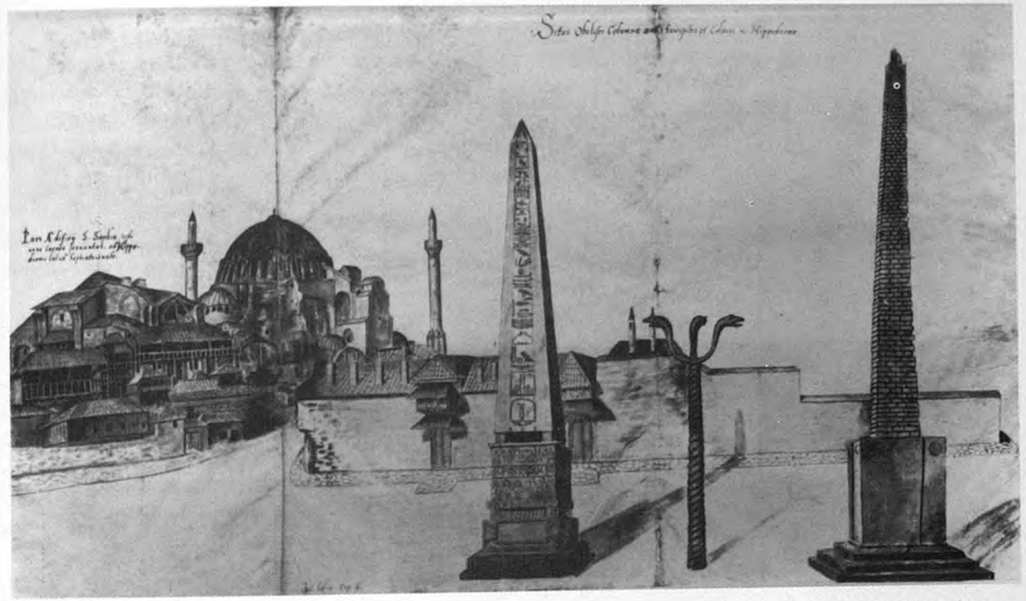


Fig. 114. The Hippodrome and Hagia Sophia, ca. 1574. (From the Freshfield Album, Trinity College Library, p. 45, ms. 0.17.2)

minarets in 1574 (Figure 114). The late-sixteenth-century Ottoman geographer Mehmed Āṣık confirms that the two minarets on each corner of Hagia Sophia's qibla wall had been built by Mehmed II and Selim II (the one that replaced Mehmed II's wooden structure) and that the remaining two identical minarets had been added by Murad III.[27]

Selim II, who wanted Hagia Sophia to be associated with his own person, transformed its image forever by deciding to increase the number of its min-

27 This source is the only contemporary information we have on the chronology of the minarets: ʿĀṣık, Meḥmed bin ʿOṣmān bin Bāyezīd, *Menāẓırü' l-ᶜavālim*, Österreichische Nationalbibliothek, Cod. Mxt. 314, fols. 262r–262v, Vienna. The same information is repeated in De Amicis, *Constantinople*, 1: 255: "One minaret was erected by Muhammad the Conqueror, another by Selim II, the two others by the Third Murad"; and in W. R. Lethaby and H. Swainson, *Sancta Sophia, Constantinople: A Study of Byzantine Building* (London, 1894), 127, where the brick minaret at the southeast corner is attributed to Mehmed II, the one on the northeast corner to Selim II, and the two on the western corners to Murad III. Müstaḳīmzāde also attributes the two identical western minarets to Murad III, stating that the one facing the Bab-i Hümayun was built by Selim II; *Tuḥfet'ül-haṭṭatīn*, 516. Without producing evidence, Ayvansarāyī confuses the issue by claiming that the brick minaret was built by Mehmed II, the one in front of Bab-i Hümayun by Bayezid II, and the other two by Selim II; Hāfiz Hüseyin Ayvansarāyī, *Hadīḳatü' l-cevāmiᶜ*, 2 vols. (Istanbul, 1865), 1: 3–4. Emerson and Van Nice remain inconclusive; they state that the southeast minaret was constructed by Mehmed II, the northeast one either by Bayezid II or by Selim II, and "though erection of one of the western pair was begun on orders issued by Selim in 1573, both, on account of his sudden death in 1574, were completed during the reign of his son Murad III"; "Hagia Sophia and the First Minaret," 31. Murad III is also credited with donating to Hagia Sophia in 982 (1574–75), probably upon the completion of the project, two calligraphic panels written in his own hand to be hung on both sides of the mihrab, two antique ablution urns said to have come from Bergama, and four marble pulpits built adjacent to the pillars supporting the dome; see Müstaḳīmzāde, *Tuḥfet'ül-haṭṭatīn*, 516; Ayvansarāyī, *Hadīḳa*, 1: 4, De Amicis, *Constantinople*, 1: 259; Lethaby and Swainson, *Sancta Sophia*, 84–5. Lubenau saw the urns filled with water from an underground source in 1587–9; *Beschreibung*, 1: 144.

arets from two to four. The four minarets around Hagia Sophia's dome appear to have been planned to reinforce the open competition with the Selimiye Mosque, built for the same sultan in the old capital Edirne between 1568 and 1574 as the culmination of the dialogue between Ottoman–Islamic architecture and Hagia Sophia that had been initiated earlier by Mehmed II. Surrounded by four minarets, the monumental dome of Selimiye, which Sinan built in 1572–3 (just when the firmans ordering the restoration of Hagia Sophia were issued), represented an attempt to surpass the unprecedented monumentality of Justinian's dome.[28] The two madrasas of Hagia Sophia, had they been completed, would have carried the long-distance dialogue with the Selimiye Mosque, also provided with two madrasas, still further.

Instead of his mosque in Edirne, it was Hagia Sophia in the capital that Selim II chose as the site of his mausoleum, a choice that explains why he wanted to leave his personal stamp on the latter monument. After the conquest of Constantinople, all Ottoman sultans had been buried in that city next to mosque complexes built in their own names. That Selim II did not want to interrupt the message of dynastic continuity communicated by these funerary mosque complexes symbolically marking the multiple hills of Istanbul is demonstrated by his decision to be buried in the walled garden enclosure of Hagia Sophia on the first hill. This unprecedented choice changed the character of Hagia Sophia from a commemorative victory monument to the sultan's own funerary mosque (Figures 115 through 117). The Ayasofya Mosque had dictated the new image of the Ottoman imperial mosques built after the conquest of Constantinople, but it was in turn reshaped to conform to that image through the addition of four minarets (a privilege reserved for sultanic mosques) and a royal mausoleum set in a walled garden. Selim II's imperial decree, which ordered the clearing of a wide space around the monument, shows an attempt to adapt Hagia Sophia to the by then standard layout of Ottoman imperial complexes, all of them occupying vast open precincts that can be seen as Mediterranean–Islamic counterparts to contemporary Italian Renaissance piazzas.

Hagia Sophia did not remain associated solely with Selim II for long; it eventually took on a more general dynastic character as other sultans came to be buried there, each in his own domed mausoleum. Sinan's student Davud built one for Murad III (d. 1595), using this as an opportunity to make minor repairs on the Hagia Sophia. An account book dated 1003–5 (1594–7) records the renewing of the lead on the domes, repairing the madrasa rooms, dependencies, large doors, latrines, and water conduits.[29] The domed tomb of Mehmed III (d. 1603) was built on the order of his son Ahmed I by the architect Dalgıç Ahmed Aga in 1017 (1608).[30] Its construction was again accompanied by re-

28 For the attempt to surpass the size of Hagia Sophia's dome in Selimiye and the competitive dialogue between the two monuments, see Muṣṭafā Sā'ī, *Tezkiretü' l-Bünyān* (Istanbul, 1897), 71–2; translated by M. Sözen and S. Saatçi, *Mimar Sinan and Tezkiret-ül Bünyan* (Istanbul, 1989), 114–16. The only other Ottoman imperial mosques with four minarets are the Üç Şerefeli in Edirne (1437–47) and the Süleymaniye in Istanbul (1550–7), in which they mark the four corners of the marble courtyard, unlike Selimiye and Hagia Sophia, where the four minarets surround the domed sanctuary.

29 For Murad III's tomb and that of his children built adjacent to it, see Müller-Wiener, *Bildlexikon*, 91, 93; Öz, *İstanbul Camileri*, 1: 30. The repair of Hagia Sophia is documented in Başbakanlık Arşivi, Maliyeden Müdevver 4517 and 5315.

30 For Mehmed III's tomb and a Byzantine baptistery converted to the tombs of Mustafa I and Sultan Ibrahim, see Müller-Wiener, *Bildlexikon*, 91, 93; Öz, *İstanbul Camileri*, 1: 30.

Fig. 115. Hagia Sophia, ca. 1586. (From the Lewenklau Album, Österreichische Nationalbibliothek, Cod. Vindob. 8615, fol. 129r, Vienna)

pairs in the Hagia Sophia, but this time more extensive ones that significantly transformed the mosque's celebrated decorative skin, which earlier Ottoman poems had so consistently eulogized. This was an important step in the ongoing Islamization of the building, a project that took several generations to complete.

An unpublished repair document from 1016–17 (1607–9) shows that Ahmed I's renovation included the replacement of lead sheets covering the dome, the renewal of glass panes and inscriptions, the addition of ceramic tile (*kāşī*) revetments, as well as the painting by decorators (*naḳḳāşān*) of the sultan's royal tribune, the minbar, the mihrab, the railings around the three galleries, as well as the dome and half-domes. The remaining interior and

Fig. 116. Hagia Sophia, ca. 1590. (From an anonymous album, Österreichische Nationalbibliothek, Cod. Vindob. 8626, fol. 162r, Vienna)

exterior walls were whitewashed, a task that required covering the whole structure with a wooden scaffolding.[31]

It was then that many of Hagia Sophia's figural mosaics, including the Pantokrator on the dome, which Cyril Mango brilliantly demonstrated to have remained in view throughout the fifteenth and sixteenth centuries, disappeared under paint. In a recent study of the Kariye Camii, Robert Ouster-

31 The beginning of the document summarizes the project as the "renovation and restoration of the noble Ayasofya Mosque, and covering with lead the domed roof, and various repairs at the exterior and interior, and the painted decoration of the dome with the half-domes and railings of the first and middle galleries, and the exterior and interior walls, and the repair of the glass panes, and the renewal of the crystal panes above the mihrab, and the scraping of the mihrab, minbar and mahfil." This entry is followed by a list of expenditures, including a large amount of wood used for the scaffolding, glass panes, oil, sandaracha resin, paints, brushes, bottles, gold leaf, nails, iron rods for windows around the dome, and iron seals of Solomon (*mühr-i Süleymān*) for suspending the oil lamps. The repairs also involved renewing the inscriptions: "repairing the holy words (*kelām-i şerīf*) of Ayasofya the Great"; Başbakanlık Arşivi, Maliyeden Müdevver 6484. The ceramic tiles (*kāşī*) that can still be seen near the mihrab carry the date 1016 (1607–8).

hout showed that there, too, the figural frescoes and mosaics survived well into the sixteenth century – Stephan Gerlach saw them in 1578.[32] Although Mango points out that many of the Hagia Sophia mosaics had been covered with paint by 1672, when Guillaume-Joseph Grelot made his drawing of the mosque's interior, he does not say exactly when this change took place (Figure 118).[33] He cites a curious report by the Spanish priest Otavio Sapienca from around 1610 according to which Ahmed I had done away with the image of God on the dome to the affliction of all Christians when its lead covering was renewed. This was allegedly prompted by some Jews who had offered the sultan a large sum of money for the original lead sheets, believed to contain a considerable proportion of silver, and had promised to replace the removed sheets with ordinary lead.[34] This observation seems to have been confirmed by Hans Jacob Amman, who saw only inscriptions at the center of the dome in 1612,[35] and by Louis Deshayes de Courmenin (1621), who noted that parts of the mosaic-covered dome were whitewashed and inscribed with large Arabic letters.[36] However, other travelers cited by Mango confuse the issue by continuing to mention the Pantokrator during the first half of the seventeenth century,[37] a discrepancy that can probably be explained by the tendency of travel literature to plagiarize earlier texts in order to boast of having seen all the marvels previously described.

In addition to the document recording Ahmed I's repairs in 1607–9, which confirms the renewal of lead on the dome and the painting of the whole monument, there is other evidence to suggest that the Pantokrator and other mosaics disappeared under paint at the time. The Polish traveler Simeon, who passed through Istanbul during the reign of Ahmed I on his pilgrimage to the Holy Land, describes in detail the images from the life of Christ, the Virgin Mary, the apostles, prophets, and patriarchs, the vestiges of which were still visible in Hagia Sophia. But even though he climbed to the dome he failed to mention the Pantokrator, an omission implying that it had disappeared by then. This is confirmed by an amusing story Simeon recounts as having occurred in 1609, when workers were repairing the dome of Hagia Sophia on the sultan's order:

> One of the workers who felt a natural urge to relieve himself, too lazy to come down, urinated into a bucket of lime and mixing this with plaster began to use it. But Hagia Sophia, unable to tolerate this disrespect, threw the man with the bucket in his hand down to the floor in front of everyone's eyes. The man's body was smashed into pieces like the corpse of Simon the sorcerer. Those who saw this event with their own eyes were terrified. When the sultan heard this event he was astonished and begged Allah, or-

32 Mango, *Materials;* see sources cited in app. 2: 117–40. Robert G. Ousterhout, *The Architecture of the Kariye Camii in Istanbul* (Washington, D.C., 1987), 6.

33 Mango writes that the face of the Pantokrator on the dome was obscured sometime before 1630 (perhaps before 1580–92), but that the figure, which disappeared by 1672, may still have been visible in 1652; *Materials,* 99;

34 Cited in ibid., 89, 122. The reference to Jews seems to be a topos. The Umayyad caliph Yazid II, who in 723 ordered the removal of icons from all Christian churches within his realm, is also supposed to have been influenced by a Jew. For the view that Jews were responsible for the development of iconoclasm in Islam, see A. A. Vasiliev, "The Iconoclastic Edict of the Caliph Yazid II, A.D. 721," *Dumbarton Oaks Papers* 9–10 (1956), 25–47.

35 Cited in Mango, *Materials,* 89, 122.

36 Cited in ibid. For Grélot's drawings of Hagia Sophia, see Guillaume-Joseph Grélot, *Relation nouvelle d'un voyage de Constantinople* (Paris, 1680).

37 Mango, *Materials,* 123–5.

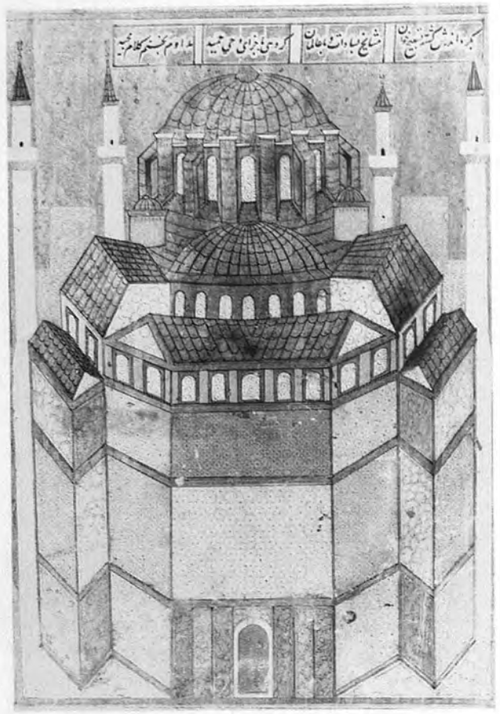


Fig. 117. Miniature commemorating Selim II's renovation of Hagia Sophia and his burial, 1581. (Seyyid Lokman, *Şehname-i Selim Han*, MS. T. K.S.A. 3595, fol. 156r)

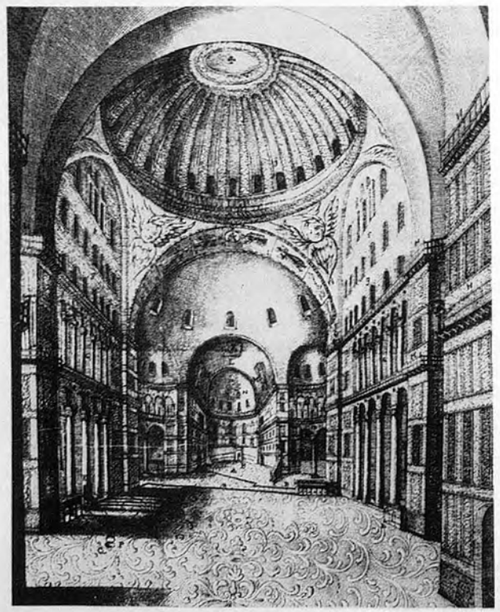


Fig. 118. Interior of Hagia Sophia looking east toward the mihrab in 1672. (From Guillaume-Joseph Grélot, *Relation nouvelle d'un voyage de Constantinople*, Paris, 1680)

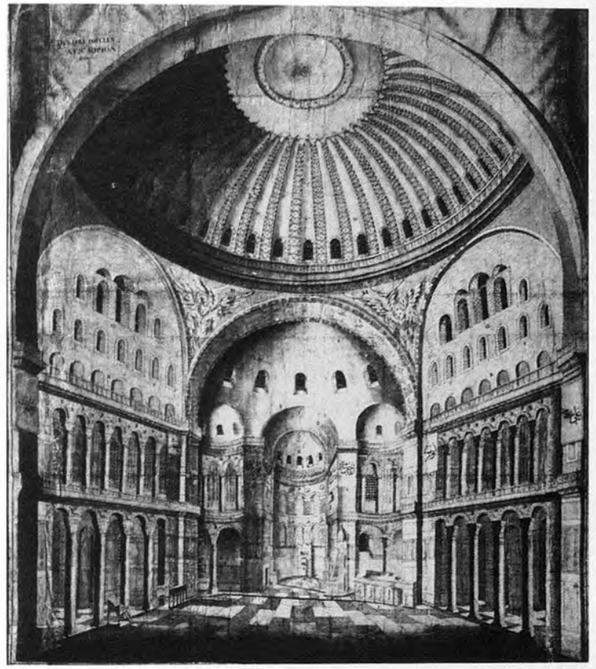
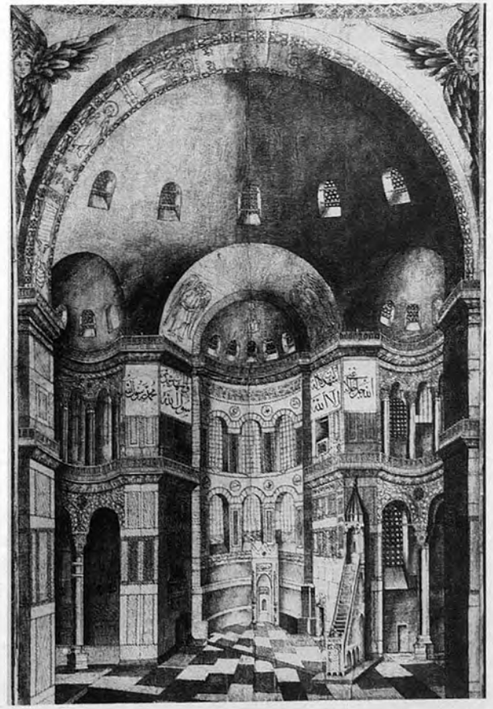


Fig. 119. (a–d) Drawings of the interior of Hagia Sophia in 1710–11 by Cornelius Loos, Stockholm National Museum. (From Alfred Westholm, *Cornelius Loos*, Stockholm, 1985)

Fig. 119a.

Fig. 119b.



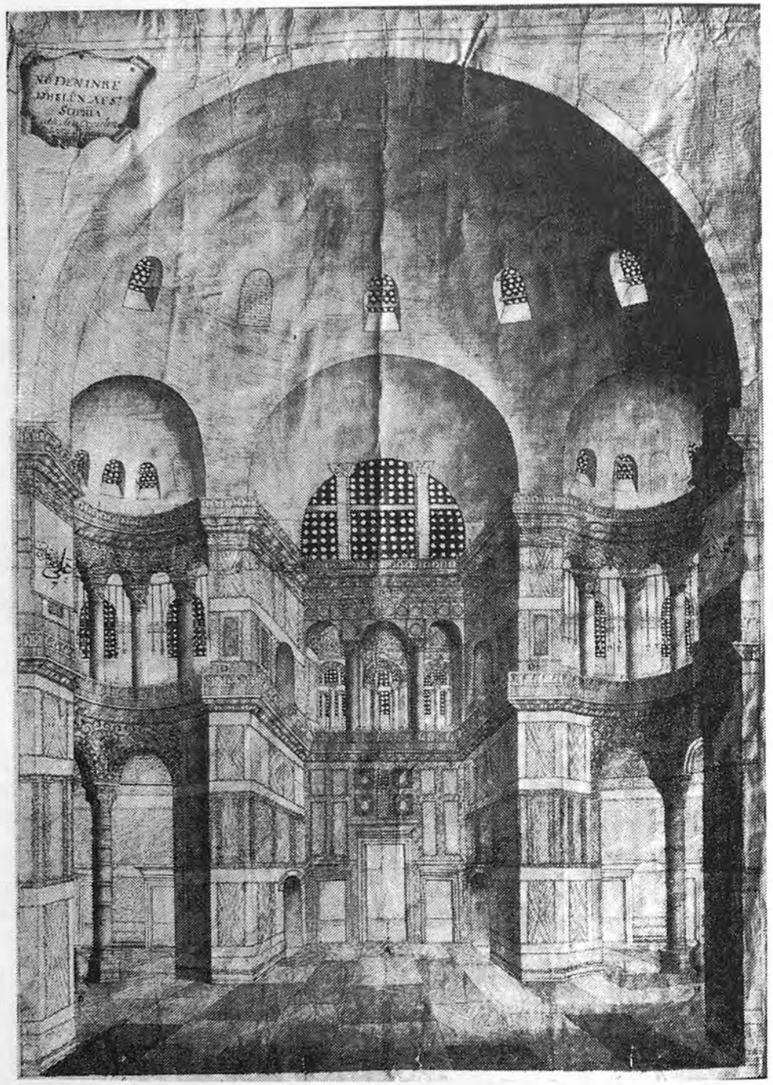
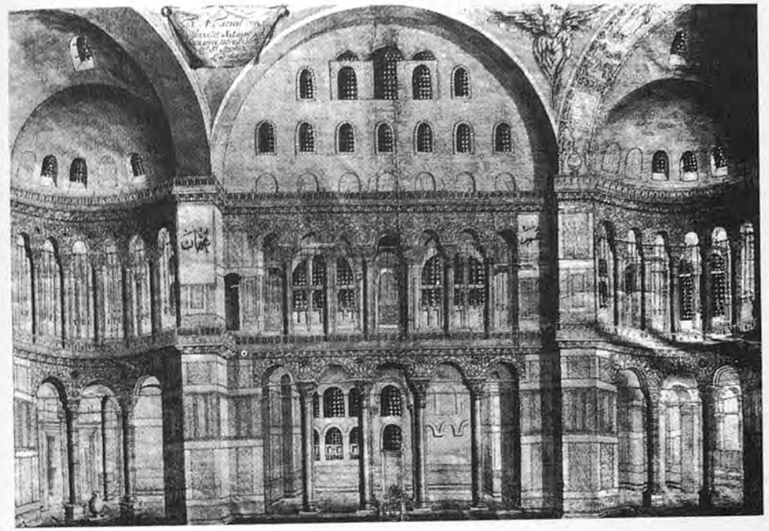


Fig. 119c.

dering that from now on nobody should show such impertinence and impudence; if anyone felt a natural urge he should come down and thus serve the sanctuary with respect and deference. Although we have not personally witnessed this event which left everyone bewildered, we heard it from the mouth of reliable Armenians, Greeks, and Turks who worked there and likewise from priests. This event occurred as a miracle to those disrespectful toward God's saints who are the honor of the Trinity and the pride of Christians.[38]

38 Simeon stopped in Istanbul three times (1608–9, 1614–15, 1618–19); his travelog is translated into Turkish by Hrand D. Andreasyan, *Polonyalı Simeon'un Seyahatnamesi (1608–1619)* (Istanbul, 1964), 5–6.



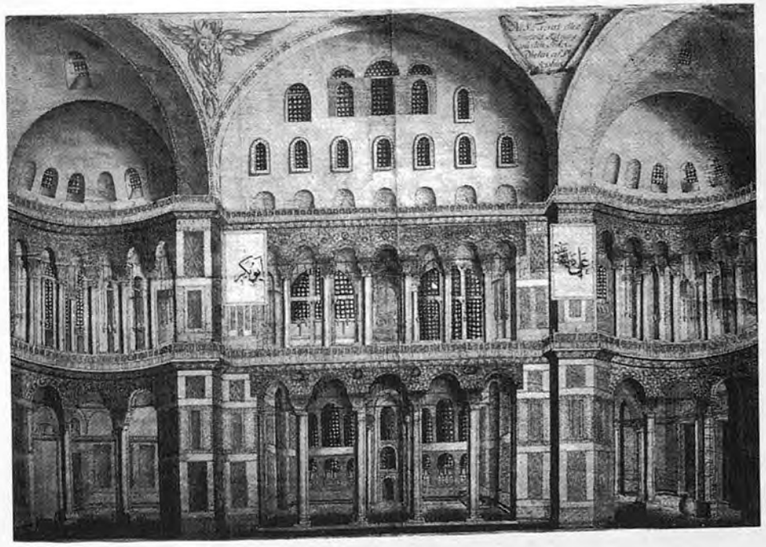


Fig. 119d.

The covering over of the Pantokrator and other mosaics in 1609 signals a growing intolerance of figural imagery in the context of a mosque.[39] Mustafa Safi, the royal imam of Ahmed I, describes in his history how the sultan broke to pieces a mechanical clock in the form of an organ with moving figurines of birds and persons holding trumpets that Queen Elizabeth of England had sent as a gift to his father Mehmed III in 1599. The sultan destroyed this object, which had been installed by the Englishman Thomas Dallam in

39 For Ottoman attitudes toward figural imagery, see Klaus Kreiser, " '. . . Dan die Türckhen leiden khain Menschen Pildnuss': Über die Praxis des 'Bilderverbots' bei den Osmanen," in *Fifth International Congress of Turkish Art*, ed. G. Fehér (Budapest, 1978), 549–56.

the Pearl Kiosk, a garden pavilion of the Topkapı Palace, because its "strange shapes and queer representations suited to heathen's temples were not tolerable in such a place of prayer and a mansion of the caliphate," a reference to the small masjid inside the kiosk.[40]

Ahmed I, described in contemporary sources as extremely devout, had turned out to be more scrupulous in conforming to the aniconic Islamic tradition than his forebears had been. However, with all his zeal, even this sultan could not bring himself to leave the walls of the Hagia Sophia totally denuded. Outside the main prayer space and beyond the congregation's field of vision, the figural mosaics were left untouched. The entire mosaic program of the inner narthex, including the lunette over the imperial door, and the vaults of the north and south galleries were still uncovered when the Swedish engineer Cornelius Loos recorded them in his drawings in 1710–11.[41]

It seems that Ahmed I had the figural mosaics of Hagia Sophia painted over selectively according to the acceptability of their iconography from an Islamic point of view. The drawings of the mosque's interior by Grélot and Loos (Figures 118 and 119 a–d) show that the only mosaics spared in the main prayer space were the four seraphim on the pendentives and the Virgin and Child in the conch of the apse above the mihrab flanked by the archangels Gabriel and Michael and framed by the figures on the great eastern arch. One wonders if the selective preservation of these mosaics was not inspired by the example of the Prophet Muhammad, who had removed all the pagon idols and painted images inside the Kaʿba except for a representation of the revered Virgin with the Christ Child sitting on her lap. Ahmed I, who had had the Kaʿba restored, might have been familiar with this tradition.[42] The consistent comparison of Hagia Sophia with the Kaʿba in Ottoman texts (perhaps because both were among the few prestigious pre-Islamic monuments reconsecrated as major Muslim shrines through the removal of idols and figural imagery) makes this hypothesis likely.

Domenico Hierosolimitano, a Jewish physician employed in the Topkapı Palace between 1580 and 1592, wrote in 1611 that a veil had been placed over the mosaic of the Virgin in Hagia Sophia so that it was not clearly visible from the prayer space below but could be observed from the gallery above; it remained uncovered because of the great veneration with which it was held.[43] The special sanctity of Mary as the mother of Christ is recognized in

40 ". . . eşkāl-i ʿacībe ve temāşīl-i ġarībeyi göricek maḥall-i buthāneler olan temāşīl ve suver bunın gibi maḥall-i ʿibādet ve menzīl-i ḫilāfetde ṭurmaḳ cā'iz ōlmaz . . ."; Muṣṭafā bin İbrāhīm Ṣāfī, *Zübdetü' t-tevārīḫ*, Ms. T. K. S. Revan 1304, fols. 39r–39v. For photographs of the relevant manuscript pages describing Ahmed I's destruction of the object, see Tülay Reyhanlı, *İngiliz Gezginlerine Göre 16. Yüzyılda İstanbul'da Hayat (1582–1599)* (Ankara, 1983), 52, 143–6. For the installation of the organ, see Thomas Dallam, "The Diary of Master Thomas, 1559–1600," in *Early Voyages and Travels in the Levant*, ed. J. T. Bent (London, 1893), 71–2, 76–80; and Stanley Mayes, *An Organ for the Sultan* (London, 1956). That clocks with mechanical figurines were tolerated by earlier sultans becomes evident in Otto Kurz, *European Clocks and Watches in the Near East* (Leiden, 1975).

41 Mango, *Materials*, 24, 99. The complete collection of Loos's drawings preserved in the Stockholm National Museum is published in Alfred Westholm, *Cornelius Loos: Teckningar fran en expedition till Främre Orienten, 1710–1711* (Stockholm, 1985).

42 A. J. Wensinck [J. Jomier], "Kaʿba," *Encyclopedia of Islam*, new ed. (Leiden, 1990) 4: 320. Azraqi's account of this tradition is cited in K. A. C. Creswell, *Early Muslim Architecture* (New York, 1979), 1 (pt. 1): 2–3. Also see Azraqi (d. 858), *K. Akhbar Makkah*, in *Die Chroniken der Stadt Mekka*, ed. F. Wüstenfeld (Leipzig, 1858), 111–13.

43 Cited in Mango, *Materials*, 88–9, 121. The image of the Virgin, which Hierosolimitano says was at the center of the dome, must be the one on the half-dome over the mihrab apse.

several verses of the Koran. On the Hagia Sophia mihrab itself, dating back to Mehmed II's reign, is inscribed the part of verse (3:37) containing the term "mihrab," possibly chosen for its reference to Mary as the mother of Christ, the very subject represented in the mosaics above.[44]

The representations of the four seraphim, archangels, and other holy personages may also have been preserved by Ahmed I for being consistent with the message of the Koran. The mid-seventeenth-century traveler Evliya Çelebi describes them as strange representations of "cherubs (*kerubiyān*) and other persons" and identifies the seraphim on the pendentives as winged angels. However, the iconography of the Pantokrator image, representing Christ as God, was more difficult to justify from an Islamic point of view. While Tursun Beg could avoid that problem by referring to it as the image of an imposing man, it was no longer tolerated by the early seventeenth century. It is unclear when the Koranic inscription roundel at the center of the dome that replaced the Pantokrator first appeared. It does not appear in the drawings of Grélot and Loos, where the central medallion is left blank with a small Greek cross in the middle, which eludes explanation (Figures 118 and 119a). Grélot describes the roundel in 1672 as "une roze, qui estoit apparemment garnie de quelque figure en Mosaique . . . mais les Turcs l'ont maintenant effacée, puisqu'il n'y paroist que du blanc." This contradicts the statements of Amman (1612) and Deshayes de Courmenin (1621), who do mention Koranic inscriptions on the dome. Since the drawings of Loos record all the other inscriptions, the one on the main dome may have been added later in the eighteenth century, as Mango concludes.[45]

The dome inscription seen today was renewed in the mid-nineteenth century by the calligrapher Kazasker Izzet Efendi. It quotes the Light Verse (24:35), which refers to Allah as the light of the heavens and the earth, an appropriate substitution for the Pantokrator image with a calligraphic representation of the nonanthropomorphic Muslim God. The Koranic passage is reinforced by the rays of gold mosaic emanating from the central disk and by the halo of light pouring in from the clerestory windows that make the colossal dome appear as if weightlessly suspended from heaven. Moreover, the Light Verse echoes the Greek inscription "Peace be with you; I am the light of the world," which remained visible up to the mid-eighteenth century on the mosaic lunette panel above the imperial door representing Christ enthroned, the very door from which the dome was meant to be viewed upon entrance to the sanctuary. This suggests that the choice of inscriptions was guided by an understanding of the iconography of the mosaics that they replaced or complemented.[46]

44 "And her Lord accepted her with full acceptance and vouchsafed to her a goodly growth: and made Zachariah her guardian. Whenever Zachariah went into the sanctuary (mihrab) where she was, he found that she had food. He said: O Mary! Whence cometh unto thee this [food]? She answered: It is from Allah. Allah giveth without stint to whom He will"; from the translation of M. M. Pickthall, *The Glorious Qur'an* (New York, 1977), 52. The use of this verse on mihrabs was not common in Ottoman mosques before the conquest of Istanbul, but it became the standard mihrab inscription thereafter.

45 Evliya, *Seyāḥatnāme*, 1: 127. Sources about the dome are cited by Mango, who concludes that the inscription roundel was probably added later in the eighteenth century; *Materials*, 89–90. It is unclear whether the Pantokrator under the calligraphic roundel was destroyed; a definite answer can be provided only by soundings in the dome; see ibid., 90–1.

46 "Allah is the Light of the heavens and the earth. The similitude of His light is a niche wherein is a lamp. The lamp is in a glass. The glass as it were a shining star. [This lamp is] kindled from a blessed tree, an olive neither of the East nor of the West, whose oil would almost glow forth [of

Loos's drawings show that the epigraphic program of the seventeenth-century mosque was concentrated on the piers supporting the dome and around the mihrab area (Figures 119a–d). The two piers flanking the mihrab apse had rectangular panels inscribed with the Sunni profession of faith (Shahāda), also repeated on the mihrab itself. Eight small roundels with the names of Allah, Muhammad, Abu Bakr, ʿUmar, ʿUthman, ʿAli, Hasan, and Husayn (the same names repeated on the piers of the dome) marked the spandrels of the arched windows above the mihrab as the aniconic Muslim counterparts to the mosaic images of apostles and church fathers that had once decorated the church. Probably dating back to Mehmed II's reign, the long inscription band flanking the mihrab quoted the Throne Verse (2:255) celebrating the absolute sovereignty of God, whose throne included both the heavens and the earth.[47] This relatively simple inscription program, deliberately kept to a minimum, was enough to communicate the orthodox Islamic identity of the mosque in which selectively preserved figural mosaics were still visible to remind the Muslim congregations of the long life of Hagia Sophia, which had witnessed the progress of religion from paganism to monotheism, a process finally sealed by the message of the Prophet Muhammad that completed the revelation of Christianity.

Ahmed I's renovation of Hagia Sophia in the early seventeenth century reflects a new ethos and ideological orientation characterized by growing emphasis on a more dogmatic interpretation of Sunni Islam. State support of religious orthodoxy had begun to play an increasingly central role in legitimizing the rule of the sultans from the late sixteenth century onward once the territorial expansion of the Ottoman Empire had slowed down. The early years of Ahmed I's reign saw the loss of territories to the Safavids in the eastern front and the loss of face in the west through the signing of the Zsitvatorok Treaty (1606) with the Austrian emperor, in which the sultan officially abandoned claims to superiority and demands of tribute. In this context, when the Ottoman state also came under constant criticism for its failure to maintain domestic law and order in the face of the disastrous Celali rebellions, the syncretism of the conquering *ghazi*s was replaced with a stricter interpretation of Islam.

In the eighteenth and nineteenth centuries, as the sultans began to present themselves officially as caliphs with claims to religious authority over the Muslim populations that had passed under Christian domination, Hagia So-

itself] though no fire touched it. Light upon light, Allah guideth unto His light whom He will. And Allah speaketh to mankind in allegories, for Allah is knower of all things"; translated by Pickthall, *The Glorious Qur'an*, 364. It is tempting to interpret the reference to God as the "Knower of all things" as an allusion to the dedication of the building to Holy Wisdom (Christ as Hagia Sophia). The interesting observation that roundels with illusionistic representations of Christ at the centers of Byzantine church domes were designed according to the position of an ideal viewer at the threshold of the gate leading from the narthex into the domed sanctuary was made by John Shearman in one of his Mellon Lectures at CASVA, Washington D.C. in the fall of 1988. The beginning of the inscription that replaced the Pantokrator on the dome of Hagia Sophia is also aligned according to the position of a viewer in the same position.

47 "Allah! There is no God save Him, the Alive, the Eternal. Neither slumber nor sleep overtaketh Him. Unto Him belongeth whatsoever is in the heavens and whatsoever is in the earth. Who is he that intercedeth with Him save by His leave? He knoweth that which is in front of them and that which is behind them, while they encompass nothing of His knowledge save what He will. His throne includeth the heavens and the earth, and He is never weary of preserving them. He is the Sublime, the Tremendous"; translated by Pickthall, *The Glorious Qur'an*, 40. Like the dome inscription, this verse refers to the supreme knowledge of God.

phia was redefined as the symbolic seat of the Ottoman caliphate. Among the new myths created at that time (showing that the mythical history of Hagia Sophia continued to evolve) was the alleged ceremony during which the Abbasid caliph al-Mutawakkil, captured after the defeat of Mamluk Egypt in 1517, passed on the Prophet's Holy Mantle to Selim I inside the mosque. The myth of the symbolic transfer of the supreme Islamic caliphate to the Ottoman sultanate in Hagia Sophia, for which there was no historical justification, began to circulate toward the end of the eighteenth century to legitimize the rule of the sultans through the legacy of the pan-Islamic caliphate.[48]

It was in this new context that the figural mosaics still visible in Loos's drawings from 1710 to 1711 were completely covered up. The French manufacturer Jean-Claude Flachat, who was in Istanbul between 1740 and 1755, wrote that everything except for the seraphim on the pendentives had been recently whitewashed. This probably happened in the reign of Mahmud I (1730–54), who extensively renovated Hagia Sophia and added several new dependencies to it, such as a library, fountain, imaret, and a school for children.[49] The mosaics remained under the whitewash until they were uncovered by the brothers Gaspare and Giuseppe Fossati, who were commissioned by Abdülmecid I to undertake a major restoration of Hagia Sophia between 1847 and 1849. This was the second major structural repair of the building 274 years after that of Sinan. The Swiss architects consolidated the dome and vaults, heightened the southeast brick minaret to conform to the other three, repaired the leaning columns, cleaned and again covered the mosaics, painting both the interior and the striped exterior.[50]

Abdülmecid, whose reign had started with the proclamation of the Tanzimat, the most important milestone in the Westernization of the Ottoman state and culture, encouraged uncovering the mosaics for repair and criticized his predecessors for having obscured these beautiful ornaments. He took advantage of the hajj (pilgrimage) to send the most fanatical of the imams of the mosque to Mecca, before he undertook the restoration.[51] He is reported to have asked that the repaired mosaics be covered in a way that would allow them to be revealed again when an opportune moment presented itself at a religiously more tolerant time. After he had seen the uncovered mosaics, he is reported to have said, "Elles sont belles, cachez-les pourtant puisque notre religion les défend; cachez-les bien, mais ne les détruisez pas: car qui sait ce qui peut arriver?"[52] Although Abdülmecid wanted the figural mosaics of the southwest vestibule and the imperial door to remain visible since they were outside the prayer hall, in the end they, too, had to be covered under pressure from those with more conservative views.[53] Only the seraphim on the pendentives were spared, but their faces were now replaced with star medallions.

The earlier toleration of figural imagery – so long as it remained above or beyond the congregation's sight while facing the mihrab – was now completely rejected by a dogmatic attitude whose roots went back to the early

48 D. Sourdel, "Khalīfa," *Encyclopedia of Islam*, new ed., 4: 944–47. For the ceremony of the transfer of the caliphate in Hagia Sophia, see Koçu, *İstanbul Ansiklopedisi*, 3: 1471. This ceremony is not mentioned in contemporary texts; Ahmed Uğur, *The Reign of Sultan Selīm I in the Light of Selīmnāme Literature* (Berlin, 1985).

49 Flachat is cited in Mango, *Materials*, 100. For the repairs of Ahmed III in 171, of Mahmud I, and of later sultans, see Müller-Wiener, *Bildlexikon*, 93–4.

50 Mango, *Materials*, 11–16. 51 Ibid., 12–14, 135. 52 Ibid., 140. 53 Ibid., 14.

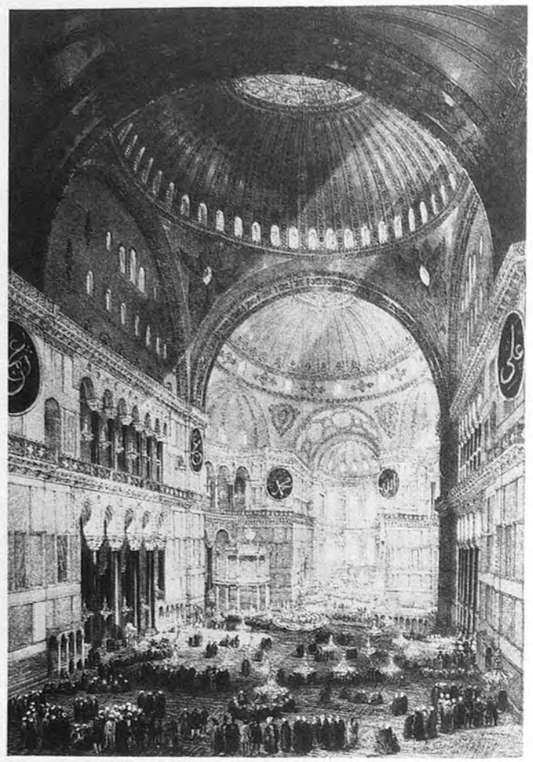


Fig. 120. Interior of Hagia Sophia looking toward the mihrab in 1849 after the Fossati restoration. (From G. Fossati, *Aya Sofia,* London, 1852, plate 3)

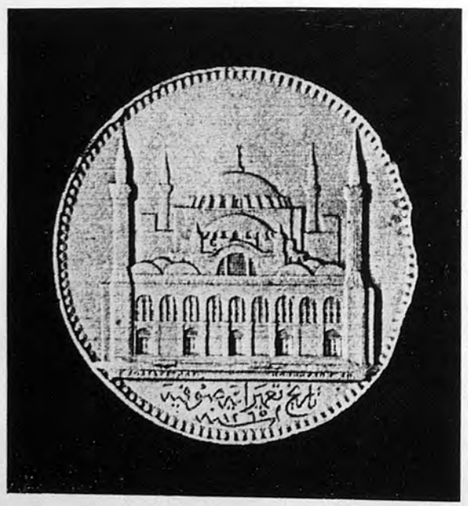


Fig. 121. Medal of Hagia Sophia commemorating the renovation of Sultan Abdülmecid.

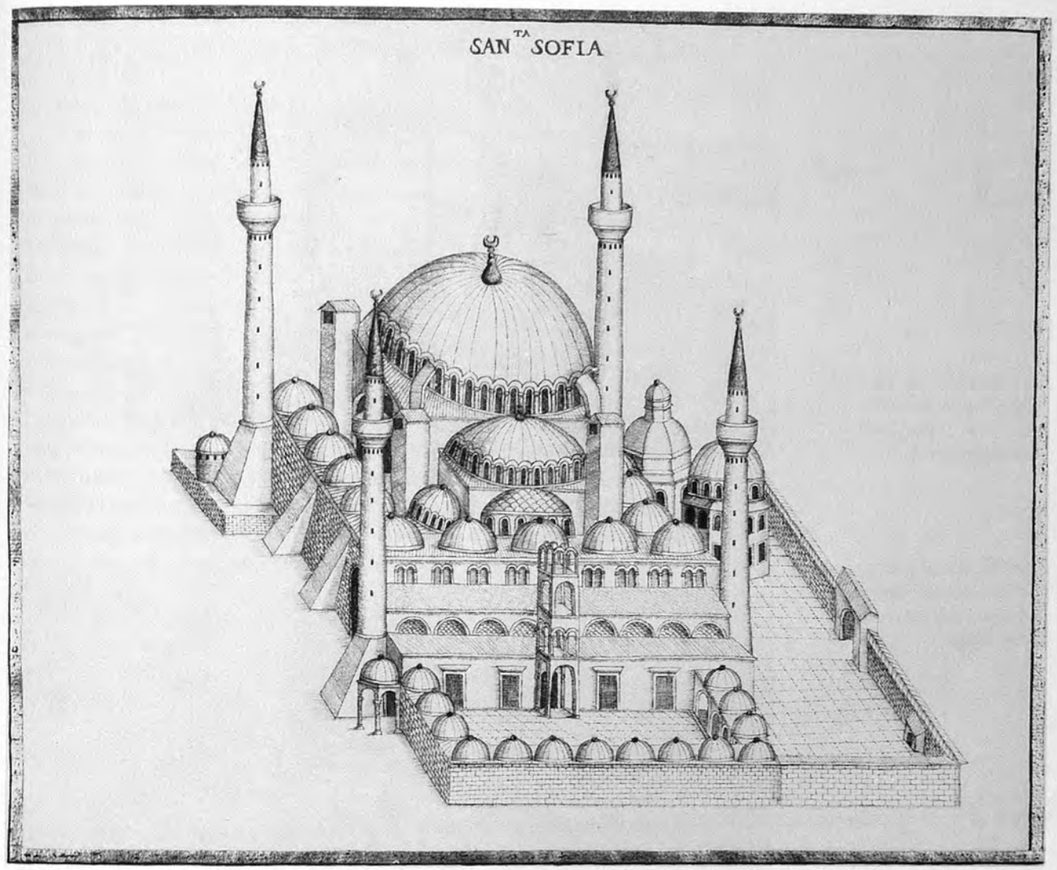


Fig. 122. Drawing of Hagia Sophia in 1686 by Francesco Scarella, *Dissegni della città di Constantinopoli*. (Österreichische Nationalbibliothek, Cod. 8627, fol. 6r., Vienna)

seventeenth century. It was during the Fossati repairs that the eight colossal calligraphic roundels with radii of nearly 8 m, which even today so insensitively dominate the mosque's interior, were created as if to proclaim Islam's power more forcefully. Composed by the calligrapher Kazasker Mustafa Izzet Efendi, these large circular placards, inscribed with the names of Allah, Muhammad, the first four Sunni Caliphs, Hasan, and Husayn, replaced the smaller seventeenth-century rectangular inscription panels bearing the same names, which had harmonized successfully with the mosque's proportions (Figures 119a–d and 120).[54] Izzet Efendi also renewed the dome inscription

54 For the large roundels, see Mango, *Materials,* 90–1. They were first composed on a small scale by Izzet Efendi and subsequently enlarged with the help of his students by the use of a square grid; Sedat Kumbaracılar, "Ayasofyanın Levhaları," *Hayat Tarih Mecmuası* 1 (1970), 74–7. The removed rectangular inscription panels are attributed to the mid-seventeenth-century calligrapher Teknecizade İbrahim Efendi; see Müstakīmzāde, *Tuḥfet-ül-ḥaṭṭaṭīn,* 48; Ayvansarāyī, *Hadīḳa,* 4. Koçu, *İstanbul Ansiklopedisi,* 3: 1451. For the tradition that they were made for Murad IV by the calligraphers Bıçakcızade Mustafa Çelebi and Teknecizade İbrahim, see Müller-Wiener, *Bildlexikon,* 93.

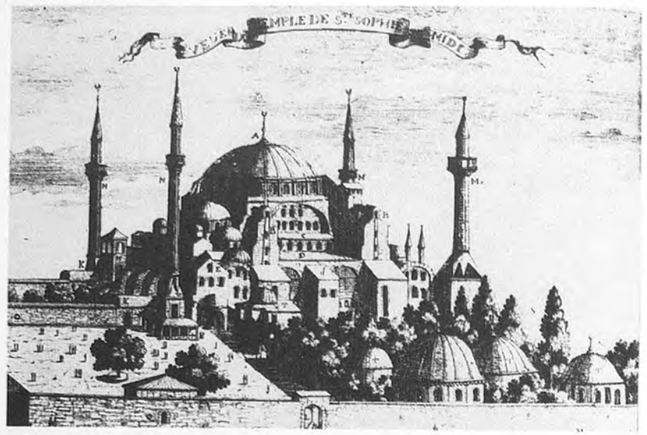


Fig. 123. Exterior view of Hagia Sophia from the southwest. (From Grélot, *Relation nouvelle*)

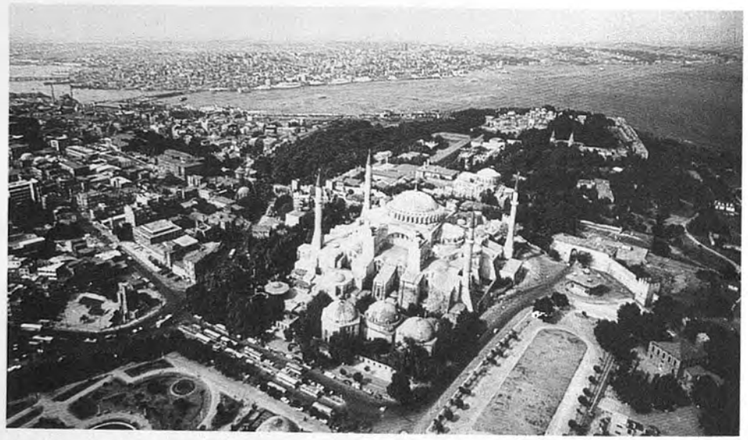


Fig. 124. Aerial photograph of Hagia Sophia with the Topkapı Palace seen in the background.

and possibly others without significantly transforming their earlier program. After the Fossati renovation, the ancient basilica became the support for aniconic Islamic signifiers that constituted a new decorative skin. The late-nineteenth-century traveler Edmondo de Amicis observed that the mosque was spread over the surface of Justinian's basilica and "hung upon its walls."[55]

For the inauguration ceremony on 13 July 1849, Abdülmecid had a commemorative medal cast in Paris, one side carrying his *tughra* (monogram) and the other an image of the mosque with the inscription "Date of the repair of Hagia Sophia 1849 (*Tārīḫ-i tāʿmīr-i Ayaṣofya, 1265*)" (Figure 121). Together with the twenty-five colored lithographs published as an album by the Fossati

55 De Amicis, *Constantinople*, 1: 258.

brothers, the European medal brought Hagia Sophia to the center of international and scholarly attention, which eventually culminated in the uncovering of its mosaics by Thomas Whittemore in 1931 and Atatürk's secularization of the mosque by turning it into a museum in 1934.[56]

The appropriation of Hagia Sophia as an imperial and religious symbol by the Ottoman sultans had involved an awareness of its former significance, as well as a shared language of architectural forms transcending the mere *prise de possession* of a Christian sacred space by Muslim conquerors (Figures 122 through 124). Its adaptive reuse is a striking example of cultural confrontation in a frontier zone where the conquerers chose to define their self-identity in terms of the conquered, while simultaneously remaining meaningful to their own past. The Ottomans had inherited both a unique building and a literary text explaining its past; they subtly transformed the two together into an integral part of their own collective memory. Hagia Sophia was therefore a true *lieu de mémoire* in which a wide variety of memories (Christian–Byzantine and Islamic–Ottoman) crystallized, passing down from one generation to the other and continually being reinterpreted according to changing contexts.[57] While it had a remarkable capacity to condense memory, Hagia Sophia was not an open signifier to which any signified could arbitrarily be attached by changing audiences. Its meanings revolving around the twin themes of universal empire and religion remained surprisingly constant before and after the conquest of Constantinople. Given the complementary role of state and religion in both the Byzantine and Ottoman empires, which shared universalistic ambitions, the colossal domed space of Hagia Sophia, designed as a microcosmic image of the universe, was always meaningful as a monumental expression of sacred and royal power. The imperial and religious associations that the Ayasofya Mosque came to acquire over 481 years of Ottoman rule had to be neutralized under the secular Turkish Republic soon after the abolition of the sultanate and caliphate. The mosque had become too closely linked with the legitimacy of the Ottoman past from which the new government chose to sever its ties. As a national museum Hagia Sophia again proved its remarkable flexibility in adapting to a new context, a flexibility that ensured its continued life through the ages.

56 For the medal, see Mango, *Materials*, 16. The album is G. Fossati, *Aya Sofia, Constantinople, as Recently Restored by Order of H. M. the Sultan Abdul-Medjid* (London, 1852).

57 The concept of *lieux de mémoire* is developed by Pierre Nora, "Between Memory and History: *Les Lieux de Mémoire*," *Representations* (special issue on memory and counter-memory) 26 (1989), 7–25. Also see Maurice Halbwachs, *The Collective Memory* (New York, 1980).

APPENDIX

SELECTED SURVEY DRAWINGS OF HAGIA SOPHIA

ROBERT VAN NICE

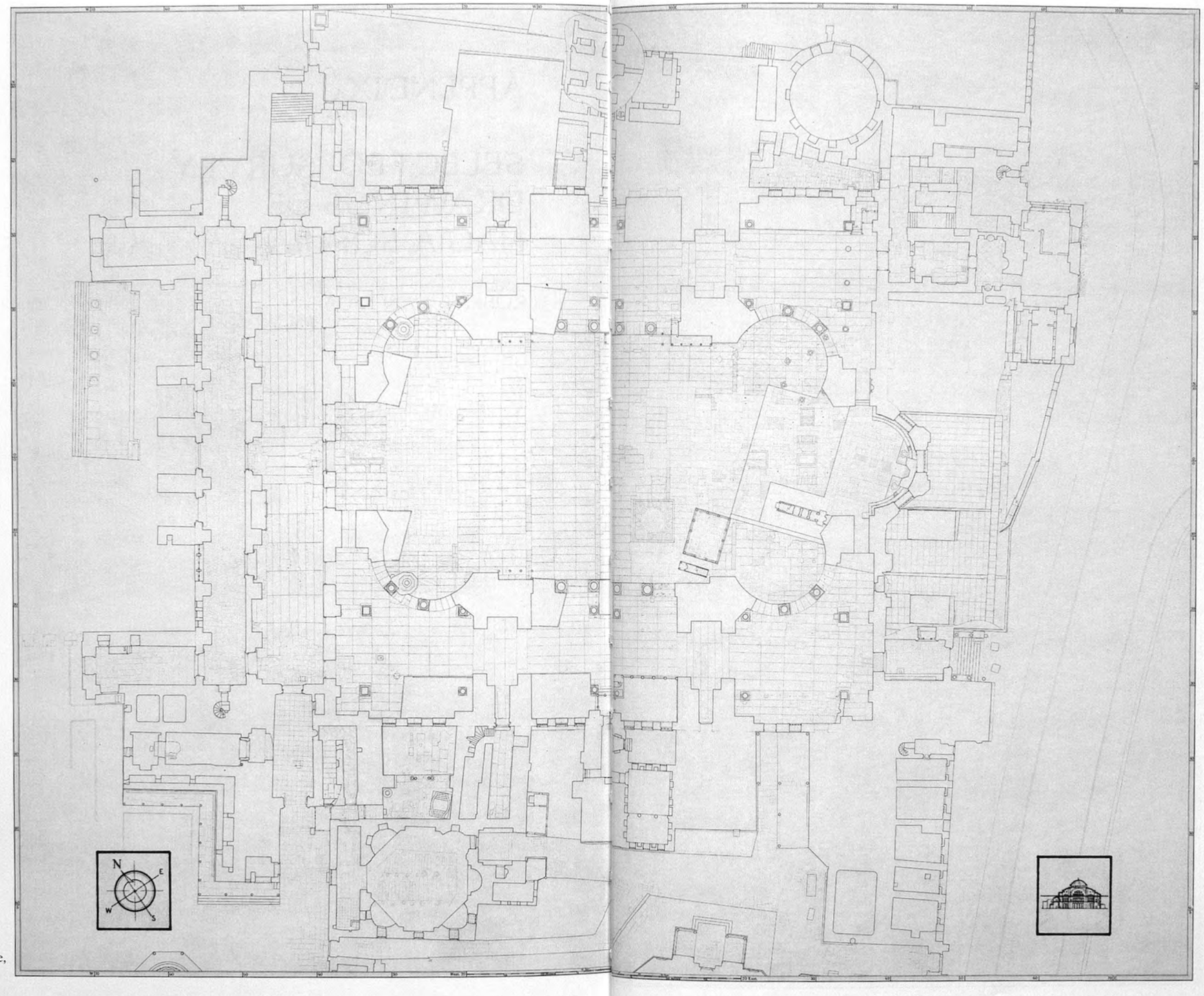


Plate 1. General plan at ground level. [Original scale, 1:250 m]

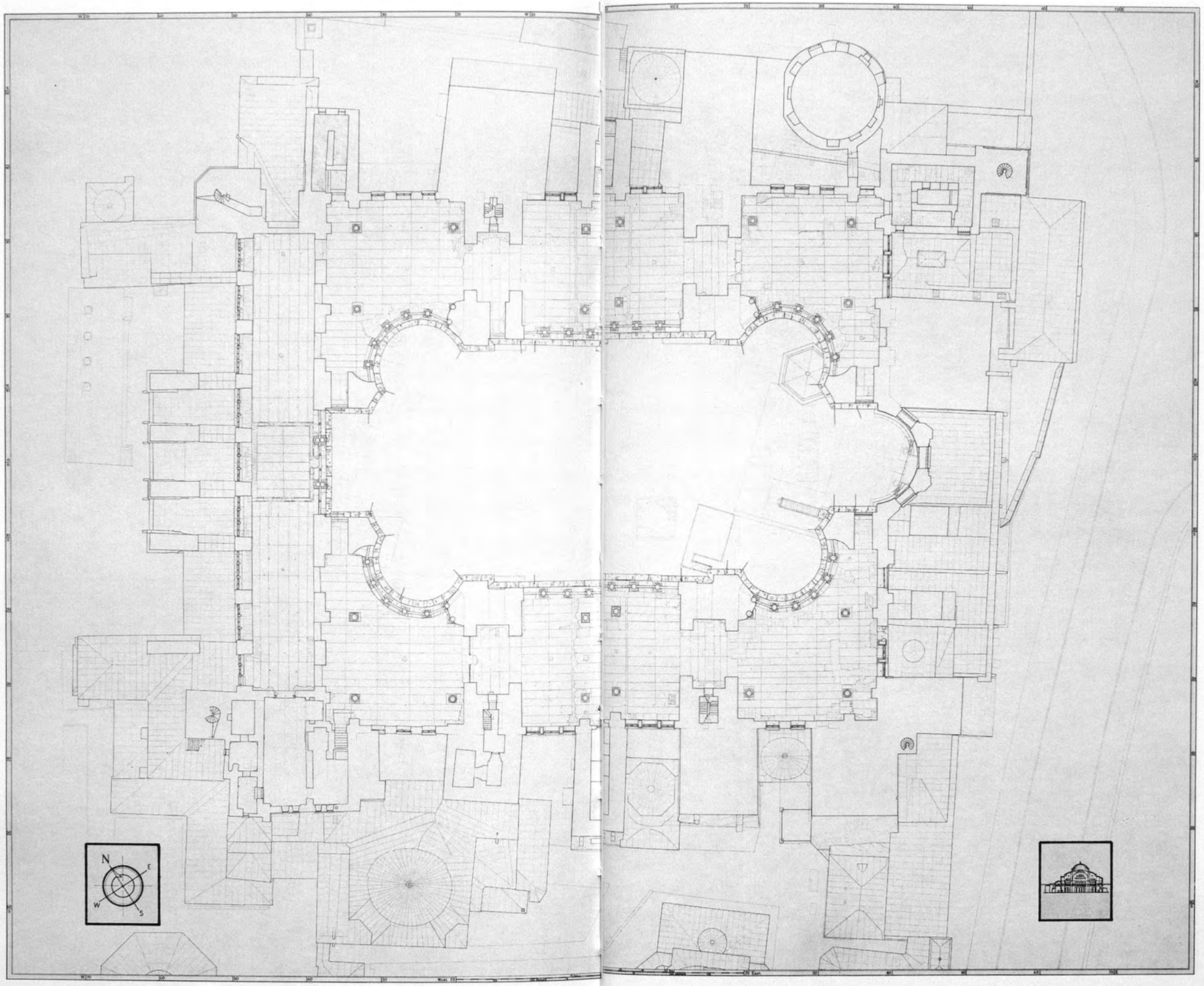


Plate 2. General plan at gallery level. [Original scale, 1:250 m]

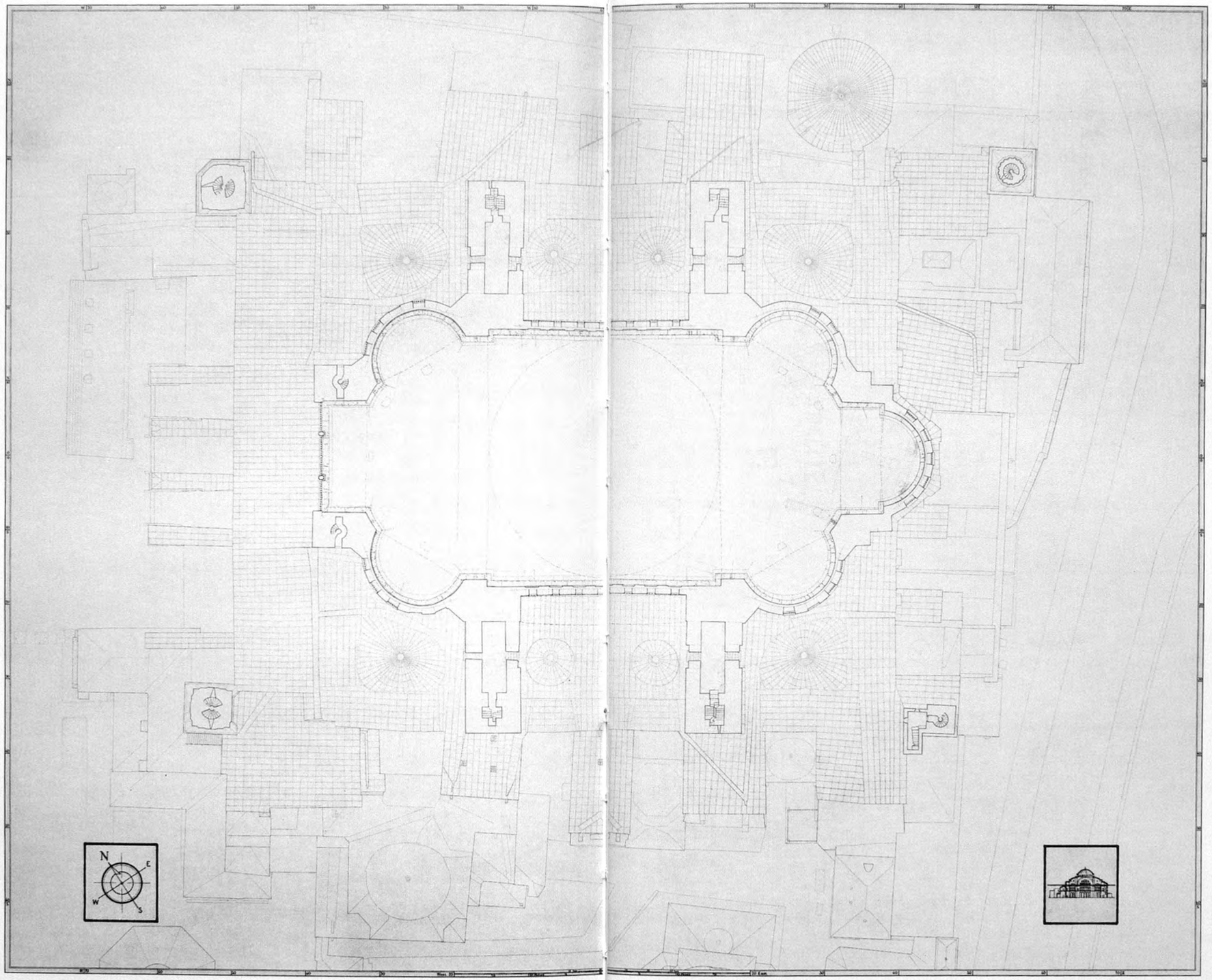


Plate 3. General plan at springings of main arches and semidomes. [Original scale, 1:250 m]

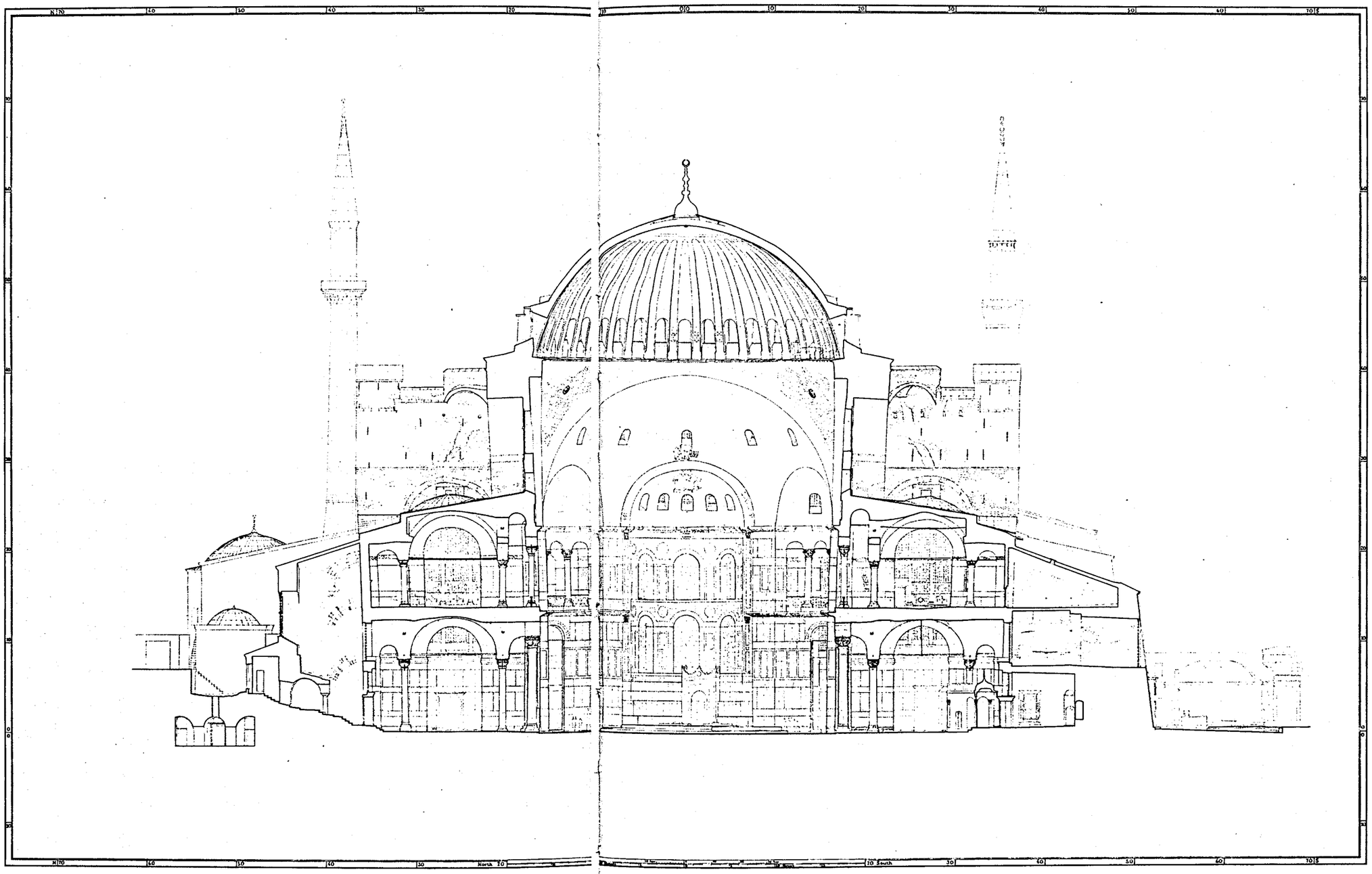


Plate 4. Transverse section looking east. [Original scale, 1:250 m]

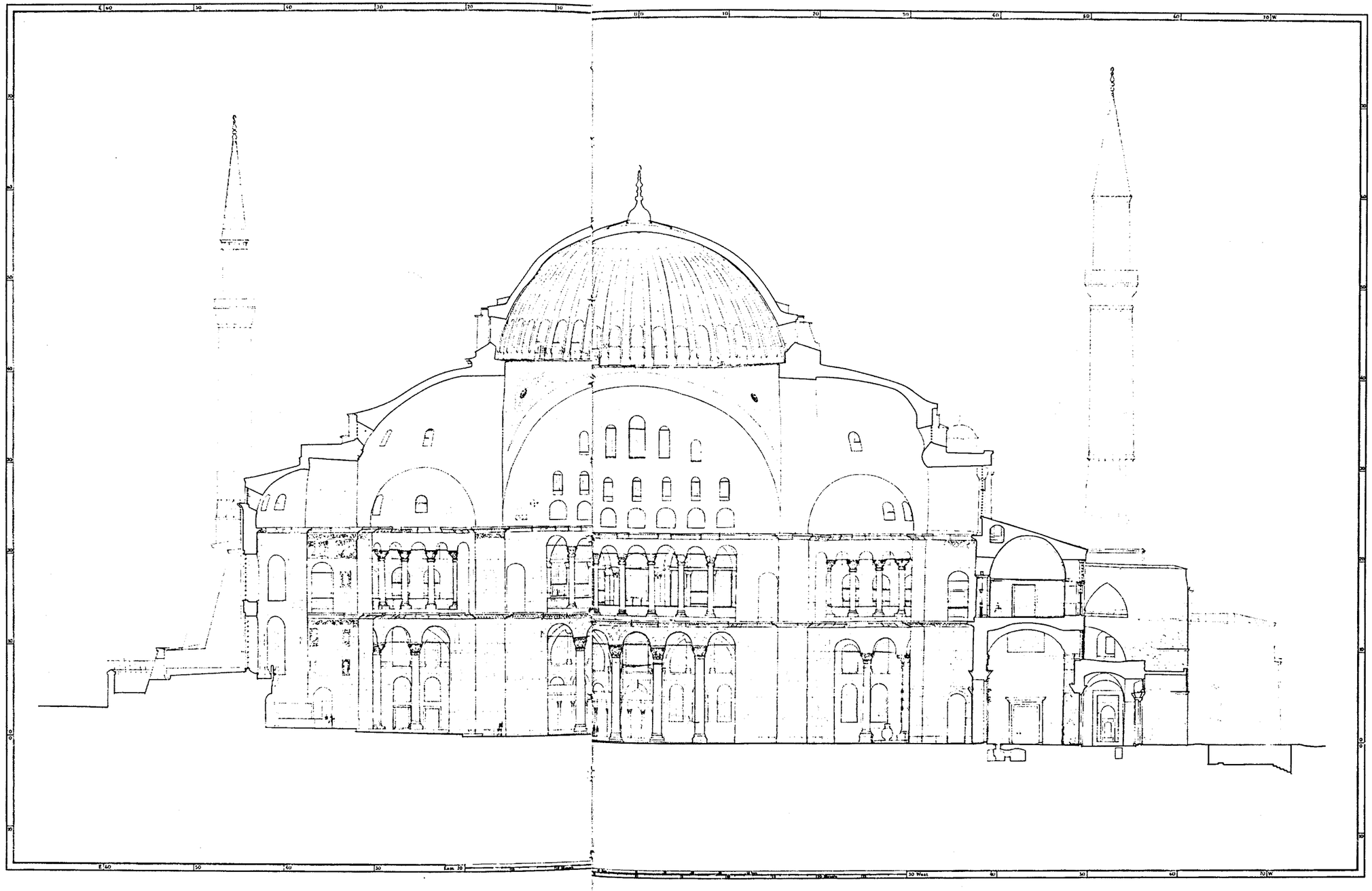


Plate 5. Longitudinal section looking south. [Original scale, 1:250 m]

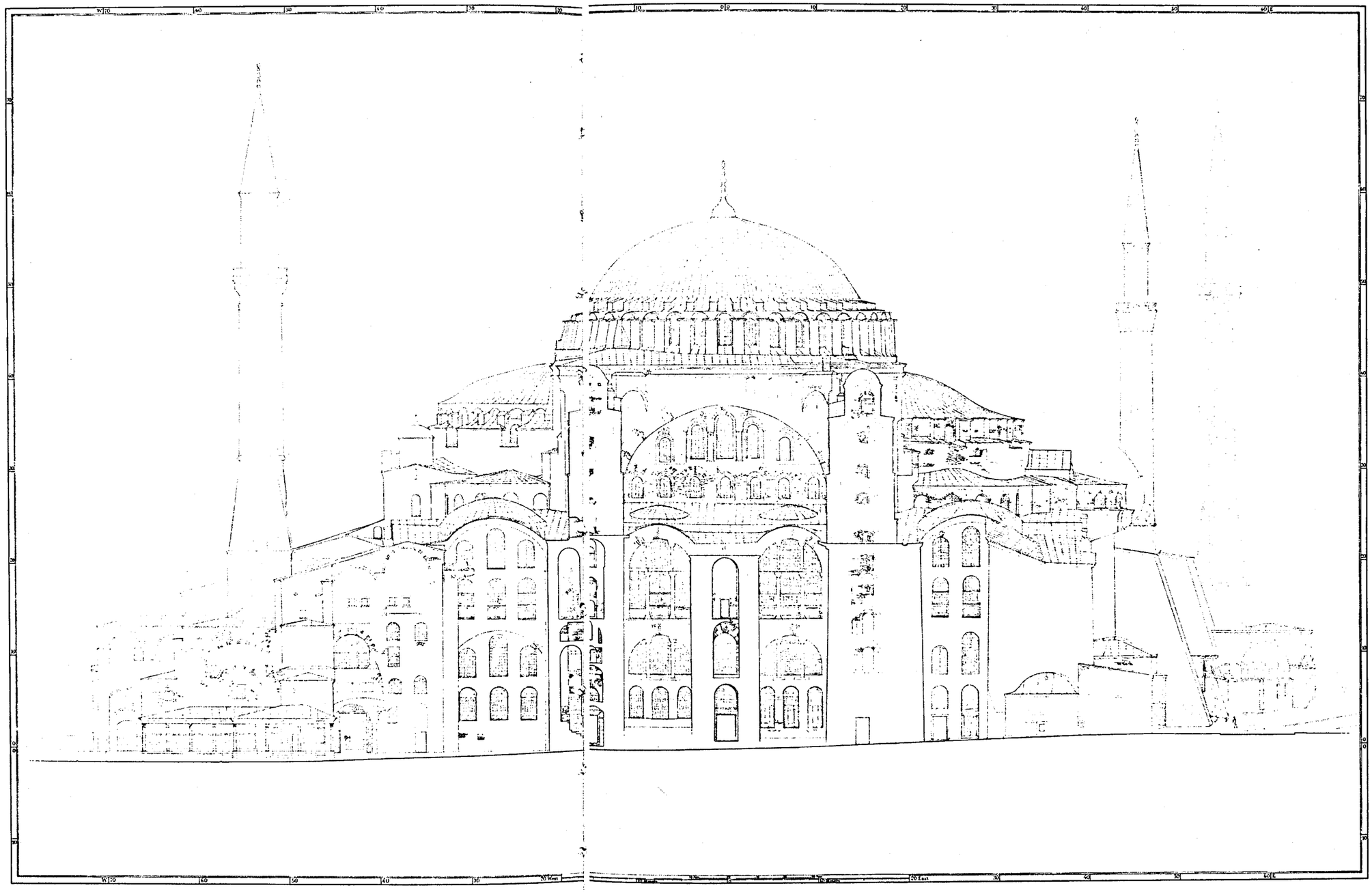


Plate 7. South elevation.
[Original scale, 1:250 m]

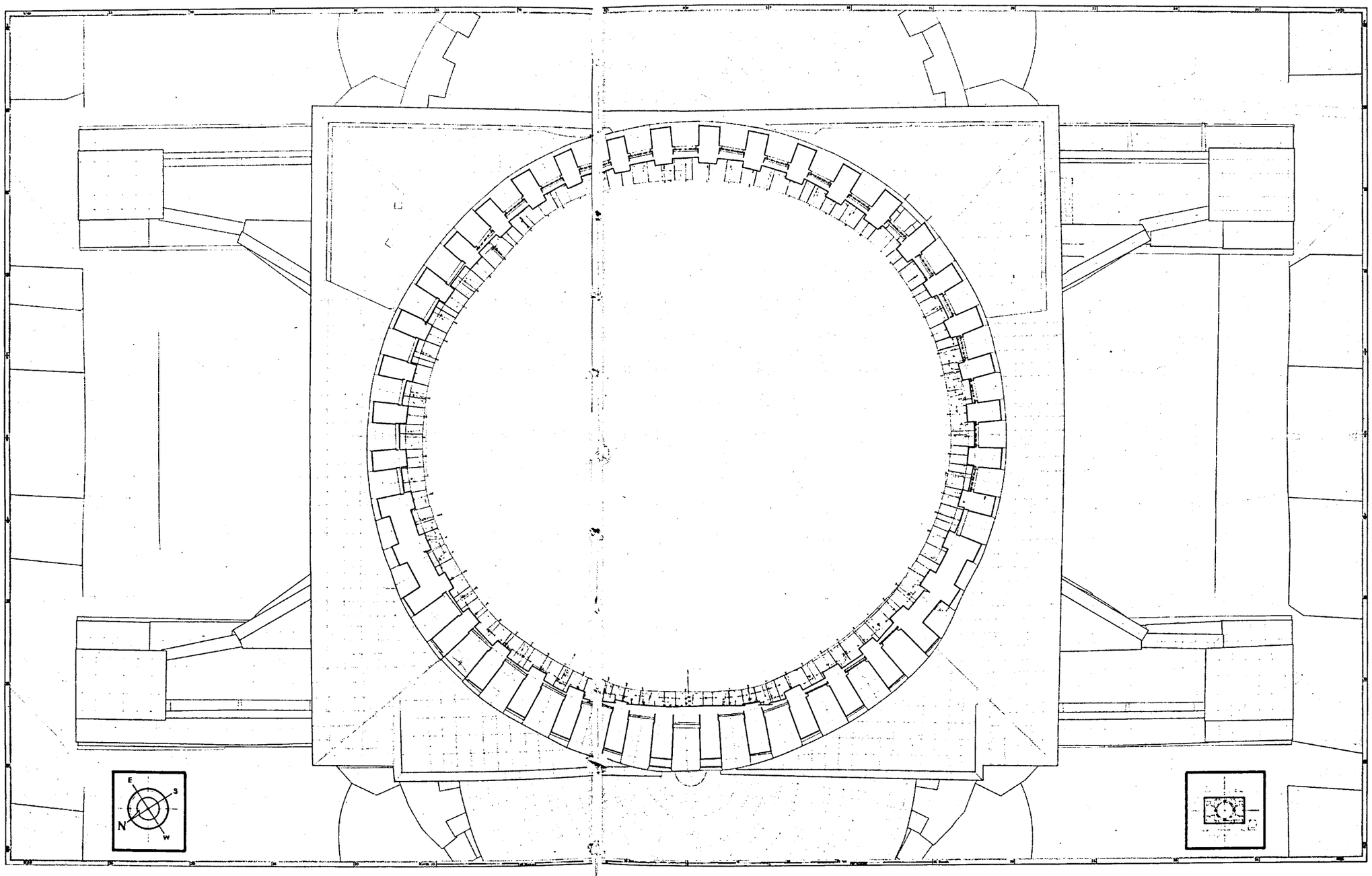
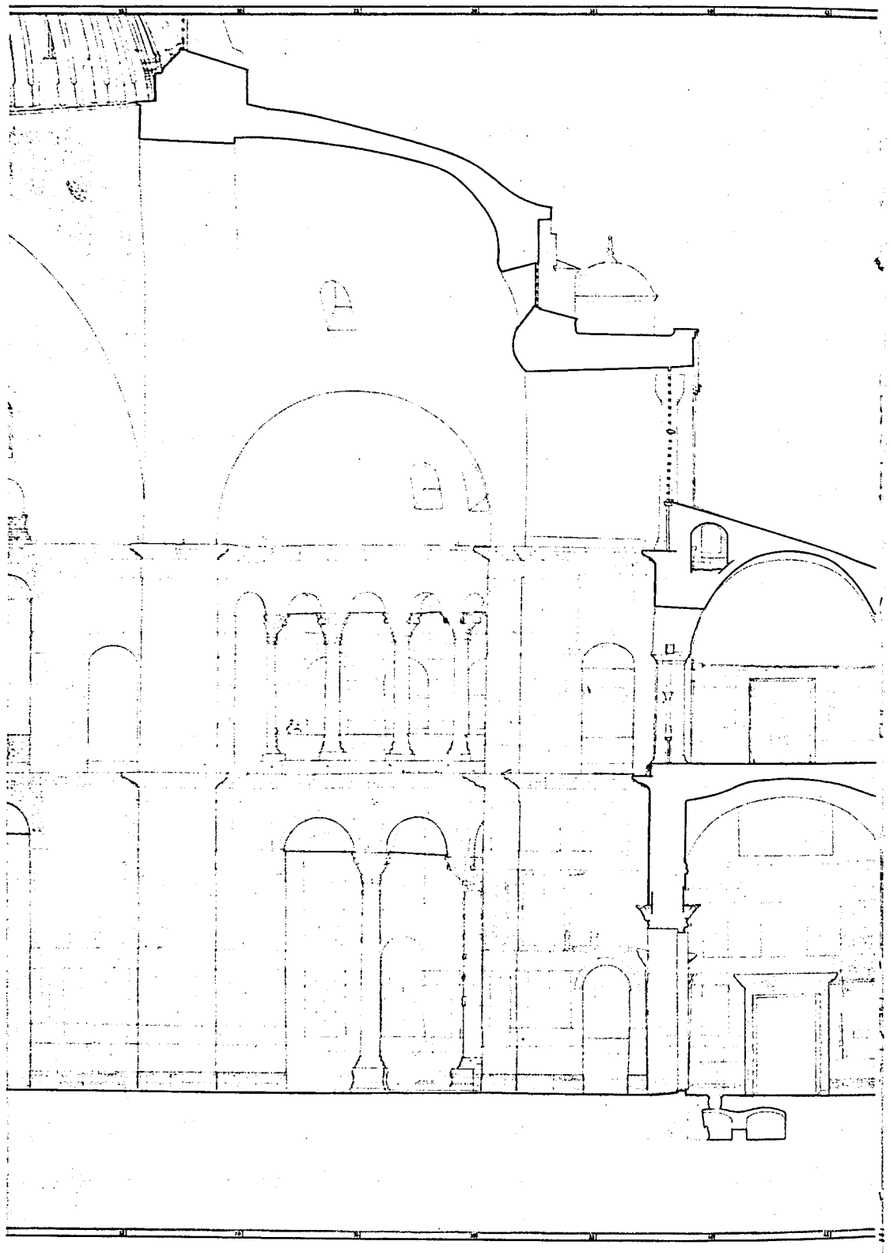


Plate 28. Plan of dome at cornice and window levels. [Original scale, 1:100 m]



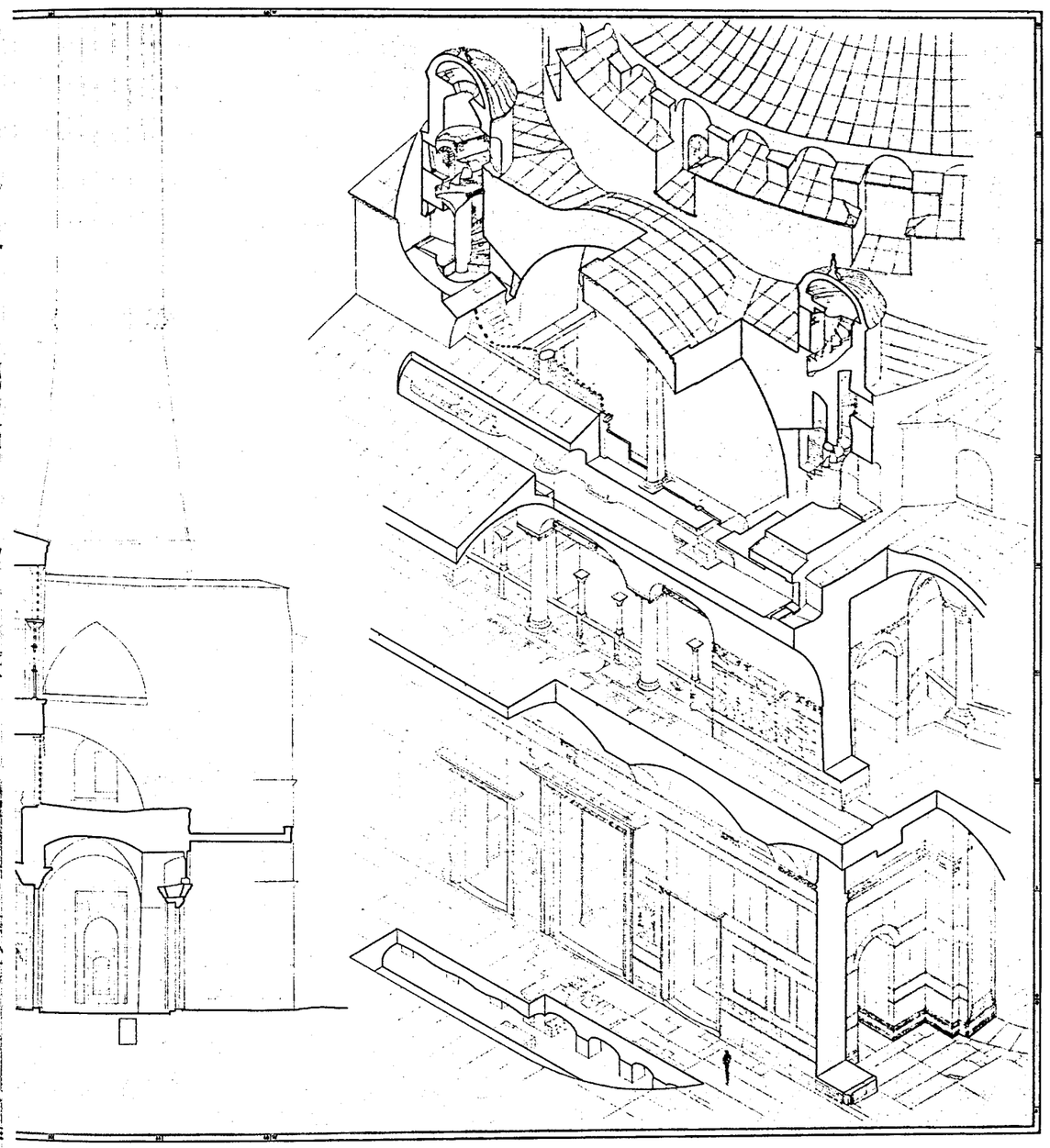


Plate 32a (left). Longitudinal section looking south. West semidome and narthexes (nave floor to dome cornice). [Original scale, 1:100 m]

Plate 32b (right). Cutaway isometric view. Imperial door, west gallery, and west window. [Original scale, 1:100 m]

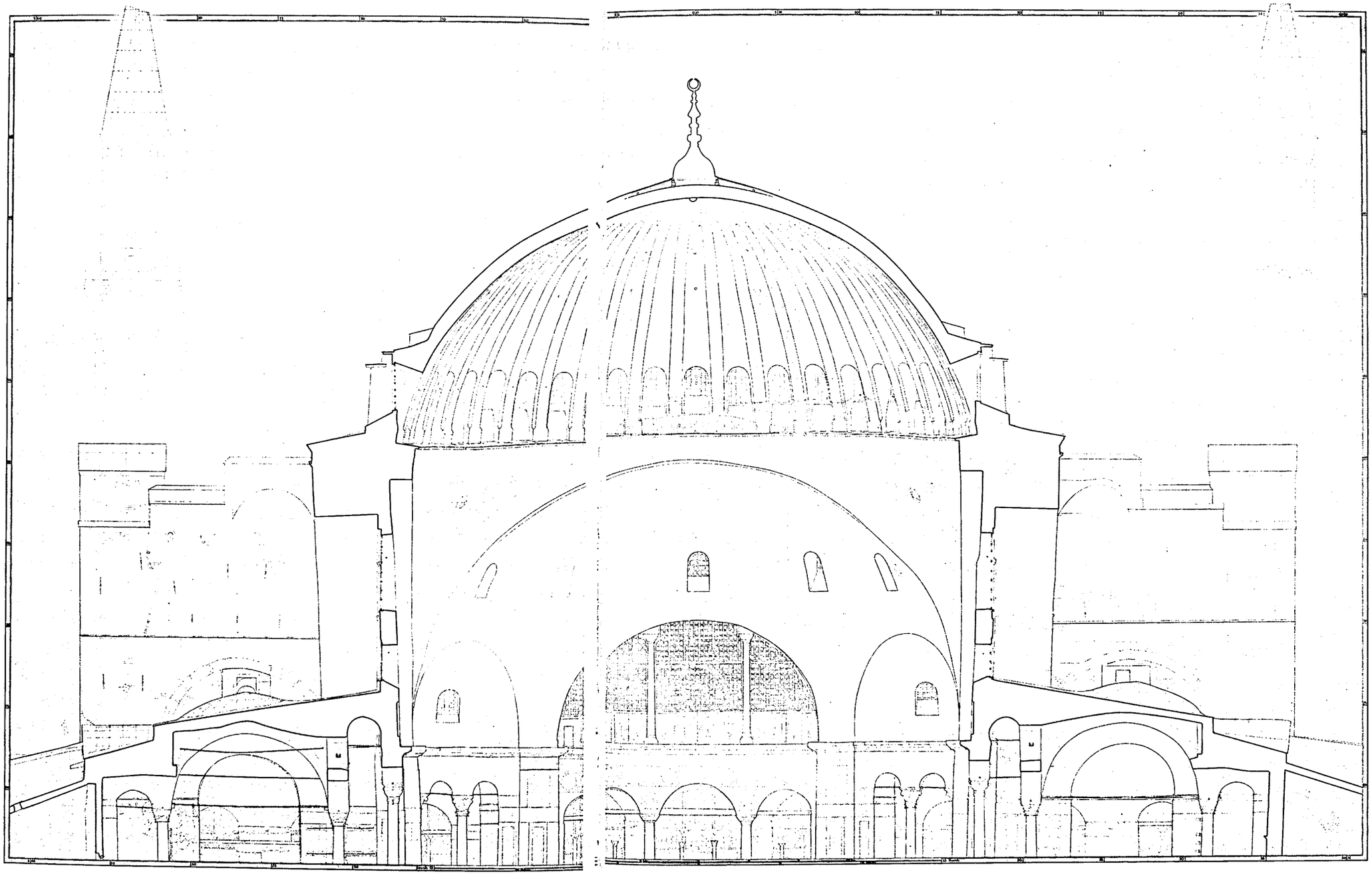


Plate 36. Transverse section looking west. Higher elements (upper parts of gallery and dome). [Original scale, 1:100 m]

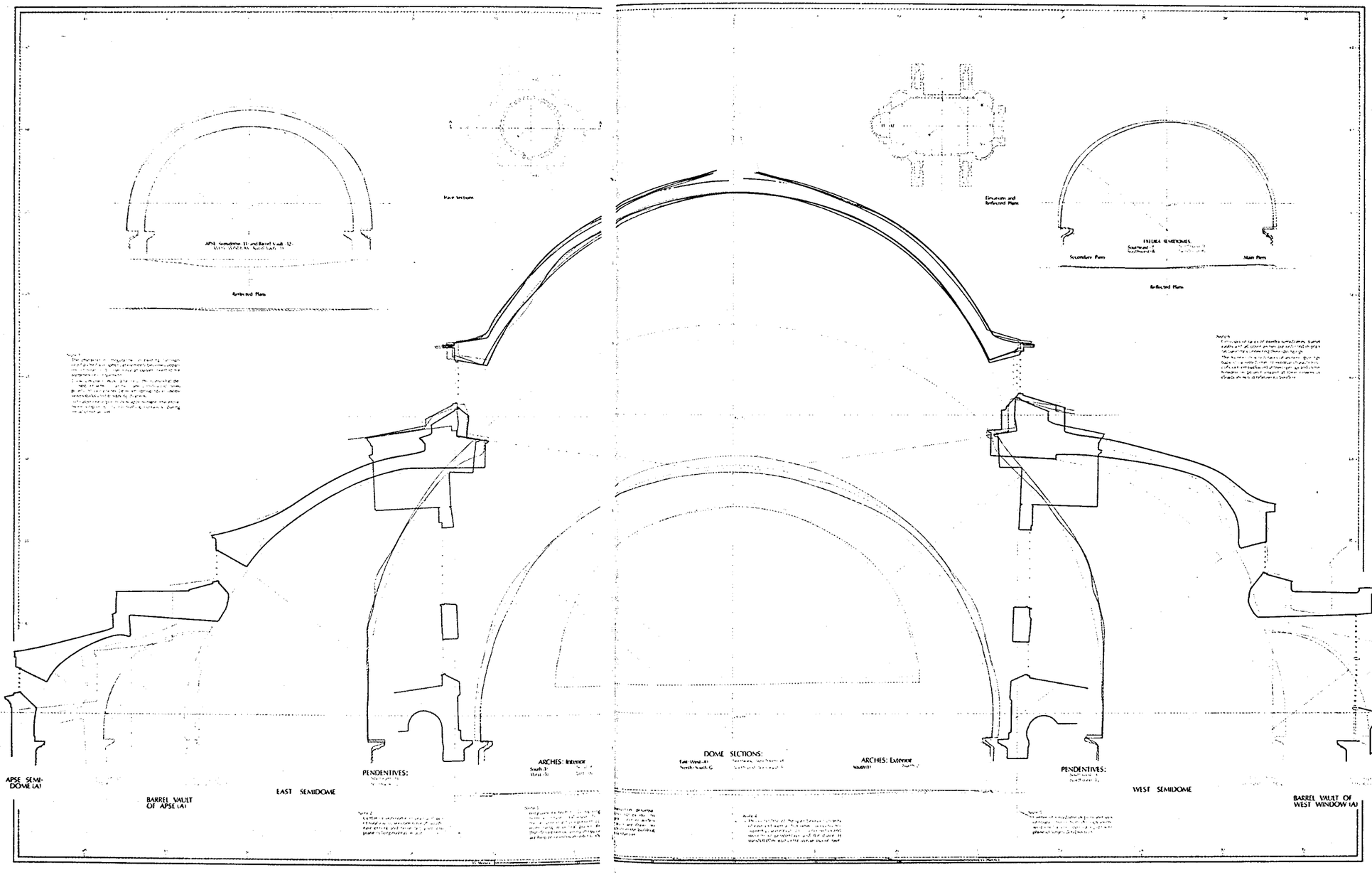


Plate 43. Main arches, pendentives, semidomes, and central dome. True contours superimposed on longitudinal section. [Original scale, 1:100 m]

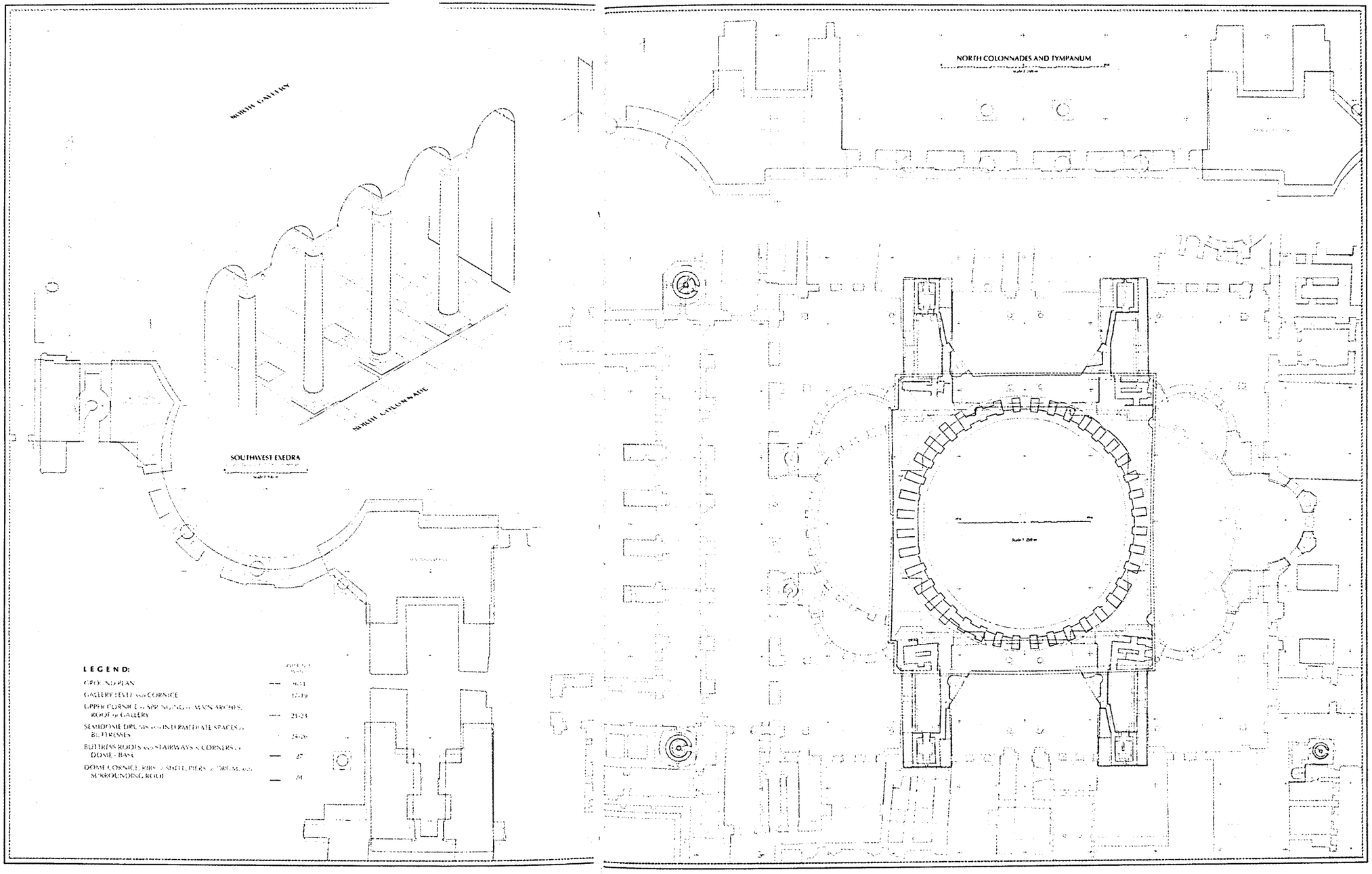


Plate 44. Trace plans superimposed, showing relation of elements at successive levels. [Original scale, 1:100]

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